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AFFDL-TR-76-78
Volume I

ADB027822

CC: B016725

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DIRECT SIDE FORCE CONTROL CRITERIA FOR DIVE BOMBING

Volume I - Summary

McDonnell Aircraft Company
McDonnell Douglas Corporation
Saint Louis, Missouri

September 1976

Final Report for Period 15 March 1975 - 15 June 1976

AD NO. ____
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Prepared for
AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

78 06 09 184

NOTICES

This technical report has been reviewed and is approved for publication.

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AIR FORCE - 15 DECEMBER 76 - 400

B0167252

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19 REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER 18 AFFDL-TR-76-78, Vol-1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 DIRECT SIDE FORCE CONTROL CRITERIA FOR DIVE BOMBING. VOLUME I · SUMMARY.		5. TYPE OF REPORT & PERIOD COVERED 9 Final Technical Report. 15 Mar 75 — 15 Sep 76
		6. PERFORMING ORG. REPORT NUMBER N/A
7. AUTHOR(s) 10 Robert V. Brulle, William A. Moran, Richard G. Marsh		8. CONTRACT OR GRANT NUMBER(s) 15 F33615-75-C-3070
9. PERFORMING ORGANIZATION NAME AND ADDRESS McDonnell Aircraft Company P.O. Box 516 St. Louis, Missouri 63166		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 82190417 17 04
11. CONTROLLING OFFICE NAME AND ADDRESS AFFDL/FGC Air Force Systems Command Wright-Patterson AFB, Ohio 45433		12. REPORT DATE 11 September 1976
		13. NUMBER OF PAGES 53
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 12 61p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government agencies only; test and evaluation; statement applied September 1976. Other requests for this document must be referred to Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; distribution unlimited.

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Direct Side Force Control (DSFC)	Flight Simulation
Wings Level Turn (WLT)	Roll About the Line of Sight (RLOS)
Lateral Translation	Pilot Workload
Airplane Design Criteria	Bomb Impact Statistics
Airplane Flying Qualities	Dive Bombing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A fixed base simulation study was conducted to determine design criteria for direct side force control (DSFC) when used for dive bombing. Three DSFC modes were simulated; a wings level turn and two lateral translation modes. A fixed depressed reticle bomb sight, a modified fixed sight that was roll stabilized, and a future impact point (FIP) computing sight were used. In addition, a control mode that rolled the aircraft about the bomb sight, line Cont'

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of sight was implemented. The simulation varied several aircraft response characteristics and control parameters to provide a large data base for analysis.

Results indicate that the DSFC wings level turn mode is the best and improves pilot acceptability and his bombing accuracy over that of a conventional roll-to-turn aircraft. The pilots were able to adapt to a large range of aircraft response characteristics using the rudder pedal for DSFC inputs. No longitudinal coupling when using DSFC should exist. Pilots can tolerate a positive roll coupling when using DSFC. A lateral acceleration of about one G should be available for a combat dive bombing using DSFC.

FOREWORD

This report was prepared for the United States Air Force by the McDonnell Aircraft Company (MCAIR), a division of the McDonnell Douglas Corporation, P.O. Box 516, St. Louis, Missouri, 63166. The study was performed under Air Force Contract F33615-75-C-3070, Project 8219, Task 0417, and was under the sponsorship of the Air Force Flight Dynamics Laboratroy (AFFDL), Wright-Patterson AFB, Ohio. Captain Jerry B. Callahan and Mr. Jerry L. Lockenour (AFFDL/FGC) were the Air Force Project Engineers.

The study was accomplished over a 15 month period from 15 March 1975 to 15 June 1976. The principal investigator was Robert V. Brulle from the Aerodynamics Department. He was assisted by Mr. William A. Moran, Aerodynamics, and Richard G. Marsh, Guidance and Control Department. The authors wish to acknowledge the help rendered by Mr. Donald C. Geers and Floyd A. Peterson from the Electronics Department for their help in setting up the bombing system network and bomb impact CEP analysis. This report was submitted by the authors 15 June 1976.

The simulation was performed in the MCAIR Flight Simulation Laboratory with Mr. Jerry J. Jones and Mr. Michael Jacezko as the simulation engineers. Special acknowledgement of their long hours spent in programming and running the simulation is extended.

Special thanks are also extended to the project pilots who sweated through the over 2500 dive bombing passes made during this study. The pilots from the 3246th Test Wing, Eglin AFB, Florida, were Maj. E. C. Newman, Capt. H. W. Powley, and LCDR S. C. Hastings, and MCAIR test pilots C. D. Pilcher and I. L. Burrows. The results of this study are based on their conscientiously expressed pilot ratings, comments and their bomb scores. We sincerely appreciated their effort.

This report is in two volumes. Volume I presents a summary of the program and results. Volume II completely documents the entire program.

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TABLE OF CONTENTS (CONCLUDED)

LIST OF ILLUSTRATIONS

List of Symbols

F_{rud}	-	Rudder pedal force
G	-	Acceleration of gravity
H	-	Aircraft altitude
n_y	-	Lateral load factor
n_z	-	Longitudinal load factor
p	-	Roll rate
δ	-	Yaw rate
s	-	LaPlace operator
V	-	Aircraft velocity
β	-	Sideslip angle
$\Delta\Psi_{RTH}$	-	Lateral aiming error
γ	-	Dive angle
Θ_D	-	Fixed bomb sight depression angle
σ	-	Azimuth or velocity vector turn angle
$\sigma\Theta$, $\sigma\Psi$	-	Elevation and azimuth aiming error standard deviation
τ_2	-	Prefilter time constant
ζ_{sp}	-	Longitudinal short period damping ratio
ζ_y	-	Lateral response damping ratio

List of Symbols (Con't)

ω_y	-	Lateral response frequency
$Kp \frac{T_1 s+1}{T_2 s+1}$	-	Quasi-linear pilot model transfer function
$K \frac{s + a}{s^2+\zeta_y\omega_y s+\omega_y^2}$	-	Low order equivalent system transfer function

Abbreviations

AFTI	-	Air Force technology integration
CEP	-	Circular error probable
DIP	-	Displayed impact point
DSFC	-	Direct side force control
FIP	-	Future impact point
HUD	-	Head up display
LT-P	-	Lateral translation - proportional
LT-I	-	Lateral translation - integral
RLOS	-	Roll about the line of sight
WLT	-	Wings level turn

INTRODUCTION

Direct side force control (DSFC) can be used to provide an aircraft with a wings level turn (WLT), a lateral translation while holding the heading constant, or for achieving a lateral fuselage aiming mode while maintaining a prescribed flight path. Incorporating these control modes on an aircraft, along with those associated with direct lift, is postulated to provide a large increase in the combat potential due to the effectiveness of these control modes in increasing the agility and preciseness of the aircraft maneuvers. In particular, simulation and flight tests of DSFC employing a WLT control mode and fixed sights have shown WLT to substantially increase the dive bombing weapon delivery accuracy and make the pilot's task easier. This increase in dive bombing accuracy was achieved using a fixed depressed reticle bomb sight. Elimination of the pendulum effect of a fixed sight was postulated as the reason for the increased accuracy.

Many types of advanced computing bomb sights are now being employed that also eliminate the bomb sight pendulum effect. The advantage of DSFC when used in conjunction with these advanced bomb sights was an unknown quantity and was a feature investigated in this study. In addition, control design requirements and flying qualities criteria were needed to allow satisfactory implementation of DSFC flight modes. This study was initiated to investigate DSFC for the dive bombing task with the objective of determining the DSFC design criteria and to measure the payoff of DSFC when used with an advanced computing bomb sight.

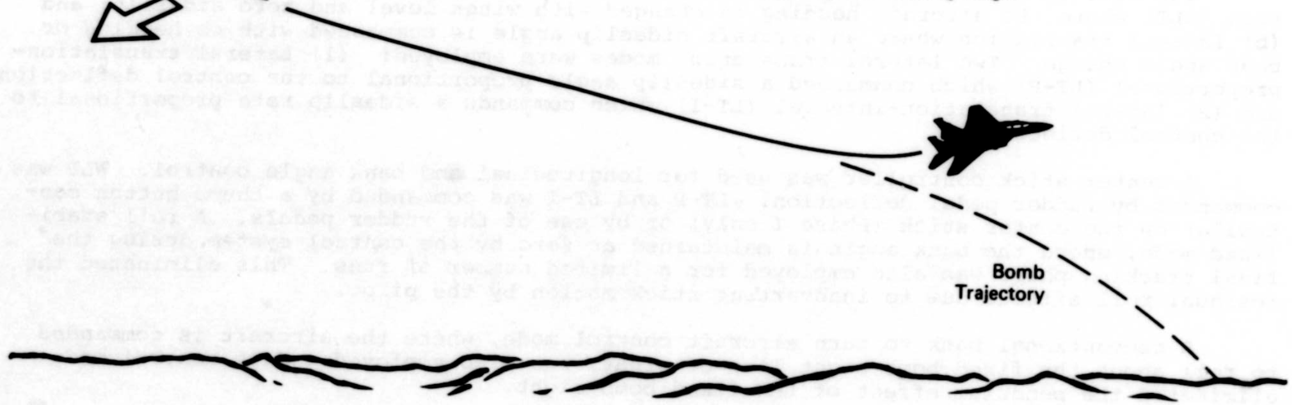
To accomplish the objective, an approach was selected that would systematically investigate the various aspects of the problem. A fixed base, two phase simulation of the dive bombing task was employed to perform the investigation. A fixed base simulation was selected over a moving base simulation because of the exploratory nature of this study, and the physiological aspects of DSFC were not considered of overriding importance at this time. A large sample of dive bombing runs were used to assure statistically significant results. A fixed roll stabilized sight and a flight control mode that rolled the aircraft about the bomb sight line of sight, both of which eliminate the pendulum effect, were incorporated in the simulation. An advanced computing bomb sight that automatically released the bomb when the release conditions were achieved was also used.

The simulation was performed in two phases. Phase I was primarily a checkout of the entire simulation including the set up, testing procedures, data acquisition and data analysis. Phase I also established satisfactory stick control forces that were then held constant for the remainder of the simulation. Phase II was the primary data gathering test.

Direct Side Force Control Criteria For Dive Bombing

Direct Side Force Control Used to Improve Bombing Accuracy Through:

1) Elimination of Bomb Sight Pendulum Effect
2) Reduced Pilot Workload for Acquiring and Tracking Target



Study Objectives:

1) Conduct Piloted Simulation to Determine Design Criteria for Direct Side Force Control Used in Air to Ground Bombing
2) Measure Payoff of Direct Side Force Control With an Advanced Bomb Sight

Accomplished By:

1) Performing a Fixed Base Simulation Varying Direct Side Force Control Modes, Configuration Parameters, Control Sensitivities and Authorities, and Response Characteristics
2) Use a Fixed and Fixed Roll Stabilized Bomb Sight Along With a Future Impact Point (FIP) Advanced Bomb Sight

DIRECT SIDE FORCE CONTROL MODES INVESTIGATED

The USAF/MDC AFTI aircraft, which has been studied and simulated for the past several years, was used as the baseline configuration for this simulation study. The AFTI aircraft configuration is characterized by having the capability to independently translate, without having to rotate, in three directions. The side force capability, the only one utilized in this study, is obtained by providing a vertical canard, which when deflected in conjunction with the vertical tail, provides a side force without rotation.

The DSFC control modes used are shown on the facing page and were: (a) wings level turn (WLT) where the aircraft heading is changed with wings level and zero sideslip; and (b) lateral translation where an aircraft sideslip angle is commanded with no heading or bank angle change. Two lateral translation modes were employed: (1) Lateral translation-proportional (LT-P) which commanded a sideslip angle proportional to the control deflection; and (2) lateral translation-integral (LT-I) which commands a sideslip rate proportional to the control deflection.

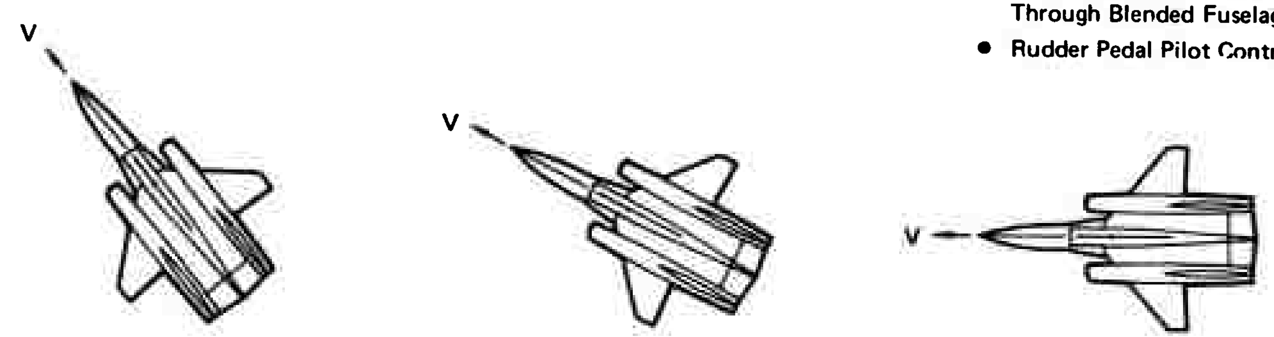
A center stick controller was used for longitudinal and bank angle control. WLT was commanded by rudder pedal deflection. LT-P and LT-I was commanded by a thumb button controller on the center stick (Phase I only) or by use of the rudder pedals. A roll stabilized mode, where the bank angle is maintained at zero by the control system during the final tracking phase was also employed for a limited number of runs. This eliminated the residual roll effects due to inadvertent stick motion by the pilot.

A conventional bank to turn aircraft control mode, where the aircraft is commanded to roll about the fixed bomb sight line of sight, was also employed. This control mode eliminated the pendulum effect of the fixed bomb sight.

Direct Side Force Control (DSFC) Modes

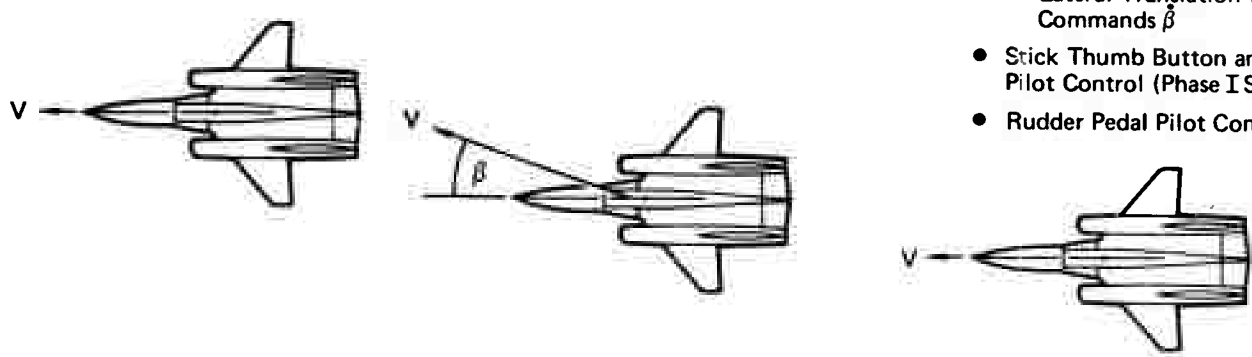
Wings Level Turn (WLT)

- Pilot Commands Lateral Load Factor and Yaw Rate Through Blended Fuselage Rotation/Translation
- Rudder Pedal Pilot Control



Lateral Translation Control

- Pilot Commands Lateral Load Factor Without Yaw Rate
  - Lateral Translation-Proportional (LT-P) Commands β
  - Lateral Translation-Integral (LT-I) Commands $\dot{\beta}$
- Stick Thumb Button and Rudder Pedal Pilot Control (Phase I Simulation)
- Rudder Pedal Pilot Control (Phase II Simulation)



- Center Stick Used for Longitudinal and Lateral Control for all Flight Modes

BOMB DELIVERY SYSTEMS

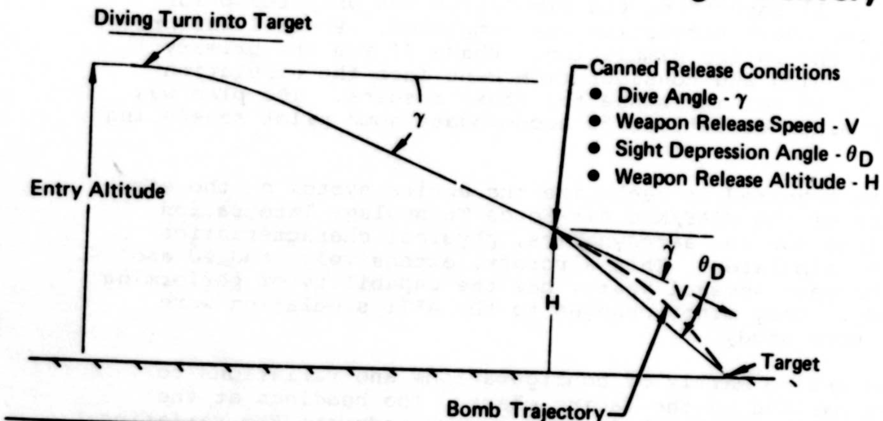
Three weapon delivery systems were implemented; (1) fixed depression bomb sight system, (2) fixed depression roll stabilized bomb sight system, and (3) future impact point (FIP) system.

Fixed Depressed Sight - The fixed bomb sight or direct delivery employs no delivery system computations. The pilot's skill and judgment are used in achieving a predetermined or "canned" delivery solution. Direct bombing is accomplished with the use of a manually depressed sight reticle. Reticle depression is based on predetermined requirements which include: altitude, speed, dive angle, and weapon type. For this concept, the pilot flies the aircraft to establish the required dive angle and ground track that intersects the target. The "pipper" must intercept the target at its canned release conditions. The fixed roll stabilized bombing is similar except that the bomb sight reticle depression line is roll stabilized to roll through an angle opposite to the aircraft roll angle. This eliminates the pendulum motion of a depressed reticle.

Future Impact Point (FIP) Sight - The FIP is a fully computed automatic bomb release system. Two bomb impact points, represented by the FIP reticle and DIP (displayed impact point) cross, are simultaneously displayed on the heads up display. The FIP reticle shows the pilot the point on the ground where the bomb impacts when released at a future time, the time being based upon a predetermined or a computed time of bomb fall. The DIP cross shows the pilot the point on the ground where the bomb impacts if released immediately. The difference between the two points as seen on the ground is range to go to bomb release which provides an indication to the pilot of time to go.

To properly use this mode of weapon delivery, the pilot maneuvers the aircraft to place the FIP reticle on the target and continues to track it thereafter using small aircraft corrections up to the time of bomb release. When the DIP cross reaches coincidence with the FIP reticle, time to go becomes zero and the bomb is automatically released if the weapons release button is depressed. Various automatic release conditions can be programmed. The release condition used for this simulation was programmed to provide a "defense clearance altitude" of 1500 ft. Immediately upon release, a 4G pullup would ensure a minimum altitude of 1500 ft.

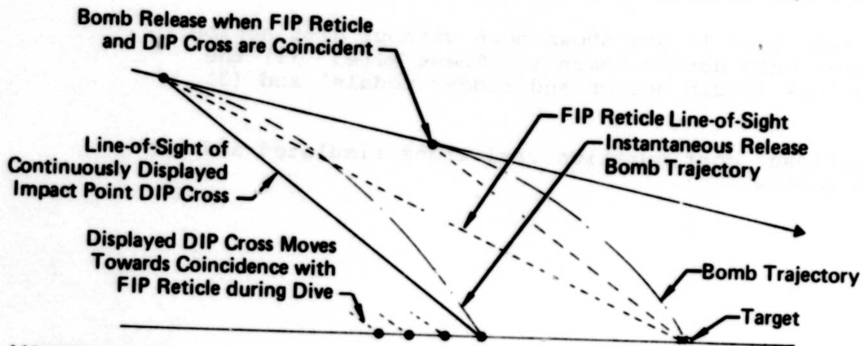
Fixed Bomb Sight Delivery System*



Fixed Sight Reticle is Depressed to a θ_D Angular Setting Corresponding to a Predetermined Set of Release Conditions for a Given Type Bomb. Bomb Release is Manual when Aircraft Reaches Canned Release Conditions of Velocity, Dive Angle, Altitude and Sight Reticle on Target.

Roll Stabilized Fixed Sight is Similar except Sight Reticle Rolled Opposite to Aircraft Roll to Keep it Stationary with Respect to Ground (Eliminates Pendulum Effect).

Future Impact Point (FIP) Delivery System*



Pilot Places Computing Bomb Sight FIP Reticle on Target and Controls Aircraft to Maintain it there. The Displacement between the FIP Reticle and the Continuously Displayed Impact Point DIP Cross Provides a Time to Go Indication. The Bomb is Automatically Released when the DIP Cross becomes Coincident with the FIP Reticle.

*Also see bomb sights in simulation test matrix charts

SIMULATION TEST PLAN

A simulation test plan outlining all aspects of the simulation was prepared prior to the running of the simulation. A two phase simulation was completed. Phase I was primarily concerned with the debugging of the entire simulation. Phase II was the primary test for data acquisition. Careful planning and consideration went into the simulation test plan to assure that the testers could not influence the final results. The plan was adhered to during the tests with only minor deviations to accommodate some pilot scheduling difficulties.

The test plan presented all data required to mechanize the entire system on the simulation facility. A simplified version of the USAF/MDC Air Force Technology Integration Aircraft (AFTI) was used as the baseline for the aerodynamics, physical characteristics and control systems implemented on the simulator. This aircraft, extensively studied and simulated by MDC for the USAF over the past several years, has the capability of performing the DSFC modes required for this study. Only minor changes to the AFTI simulation were required to implement the set up for this study.

The test plan also detailed the entire matrix of configurations and variations to be simulated. This test matrix is summarized on the facing chart. The headings at the top of the page are the four major control modes tested. Under each mode are the variatins tested with that mode. Notice that all variations were not tested with all modes. The box at the bottom of the page shows which modes and variations were tested with the various sights. All variations were tested with the FIP sight but only some of the major variations were tested with the fixed sight.

Variations tested during Phase I and Phase II are shown here without distinction. Three of the variations listed were tested only during Phase I. These were: (1) the stick feel system, (2) controller variations (thumb button and rudder pedals) and (3) tracking time.

Further amplification of the significant configuration variations simulated and the range of variables that were considered follow.

DSFC Test Matrix Summary

Conventional Mode (Roll to Turn)

- Lateral Variations
  - Stick Feel System
  - Roll about the Line of Sight
- Longitudinal Variations
  - Short Period Damping
  - Stick Feel System
- Tracking Time

Wings Level Turn Mode

- Lateral Variations
  - Stick Feel System
  - n_y Frequency and Damping
  - n_y Sensitivity/Authority
  - Roll Stabilization
- Longitudinal Variations
  - Short Period Damping
  - Stick Feel System
- Coupling
  - n_z Coupling
  - Roll Coupling
  - Sideslip Coupling
- Tracking Time

Lateral Translation Integral Mode

- Lateral Variations
  - n_y Frequency and Damping
  - n_y Sensitivity/Authority
  - Controller Variations
  - Roll Stabilization

Lateral Translation Proportional Mode

- Lateral Variations
  - n_y Frequency and Damping
  - $\beta(\sigma)$ Sensitivity/Authority
  - Controller Variations
  - Roll Stabilization
- Longitudinal Variations
  - Short Period Damping
- Coupling
  - n_z Coupling

Bomb Sights	Modes and Variations Used with Each Sight			
	Conv	WLT	LT-I	LT-P
Fixed	All Conventional Variations Except Stick Feel System	Baseline Configuration Short Period Damping Sensitivity/Authority Tracking Time	Baseline Configuration	Baseline Configuration
Roll Stabilized	Baseline Configuration Short Period Damping	None	None	None
FIP	All	All	All	All

TEST MATRIX

Stick Feel System Studies - These variations, conducted during Phase I, were directed toward defining the optimum lateral and longitudinal stick feel characteristics for the conventional and DSFC flight modes. Three variations corresponding to high, medium, and low gradients (lb/G or lb/deg/sec) were run using the conventional flight mode and FIP bomb sight. These values are shown on the upper two charts of the facing figure for the longitudinal and lateral stick motions. The relative gradients in each variation are the same for both the lateral and longitudinal motions (e.g., high lateral gradient and high longitudinal gradient) to keep the forces balanced.

The stick feel characteristics chosen by the pilots were evaluated in the DSFC WLT flight mode using the FIP bomb sight. Two additional variations (not shown) were also run for baseline verification in which the longitudinal and lateral gradients were 25% more and 25% less than the selected baseline.

The baseline gradients were chosen by the pilots as being acceptable to all and were used for the remainder of the simulation.

DSFC Authority/Sensitivity Variations - The effect of variations in rudder authority and sensitivity in the DSFC WLT flight mode was examined throughout the range of values shown in the lower left chart. The authority was increased from 1G to 3G's with corresponding changes in rudder sensitivity (lbs/G). Three variations of rudder sensitivity with the rudder authority held constant at 1G were also made.

The rudder pedals were evaluated as an alternate control input for the lateral translation flight mode, during Phase I using the FIP bomb sight (lower middle and right chart). Variations in authority and sensitivity were included in both the proportional and integral control modes and were 4.4, 8.8 and 12.0 deg max authority for the proportional mode and 2.2, 4.4 and 6.0 deg/sec max authority for the integral mode with corresponding sensitivities for an 84 lb rudder input force were implemented. The authority corresponds to the maximum sideslip angle command in the proportional control mode and the maximum sideslip angle rate command in the integral control mode. Pilot comments were evaluated to determine optimum authority/sensitivity combinations in both control modes.

Based on pilot comments obtained during Phase I, the values indicated with an * on the facing figure were selected as baseline for Phase II. Additionally, investigations of decreased and increased rudder pedal control sensitivity over the selected baseline value were conducted during Phase II in conjunction with some response variations. A WLT mode decreased rudder pedal control sensitivity value of 77 lb/G and an increased value of 21 lb/G were tested along with a LT-P value of 6.9 lb/deg (increased sensitivity), and a LT-I value of 25 lb/deg/sec (decreased sensitivity).

Simulation Test Matrix

- Pilot Control Feel System

Longitudinal Stick (1.7 lb Breakout Force)			
Variation	Gradient (Lb/G)	Maximum Force (Lb)	
		Aft	Fwd
Baseline	4.25	40.0	15.9
Low	3.5	33.0	13.4
High	7.0	65.0	25.1

Lateral Stick (2.0 lb Breakout Force)		
Variation	Gradient (Lb/Deg/Sec)	Maximum Force (Lb) Left and Right
Baseline	0.053	11.4
Low	0.036	8.4
High	0.105	20.8

Rudder Pedal Feel System Held Constant at a Gradient of 44 lb/in., Maximum Force of 117 lb with a 7 lb Breakout Force

- DSFC Authority and Sensitivity

WLT Rudder Deflection Commanded a Lateral Load Factor n_{y_c} - G's	
$n_{y_{c_{max}}}$ (G's)	Gradient (Lb/G)
1.0	43.0, 77.0, and 110.0
2.0	38.5
3.0	25.7
1.4	77.0
2.9	38.5 *
5.2	21.0

LT-P Rudder Deflection Commanded a Sideslip Angle β - Deg	
$\beta_{c_{max}}$ (Deg)	Gradient (Lb/Deg)
4.4	17.5
8.8	8.8
12.0	6.4
11.4	9.6 *
16.0	6.9

LT-I Rudder Deflection Commanded a Sideslip Rate $\dot{\beta}$ - Deg/Sec	
$\dot{\beta}_{c_{max}}$ (Deg/Sec)	Gradient (Lb/Deg/Sec)
2.2	35.0
4.4	17.5 and 25.0
6.0	12.8
6.1	17.5*

*Selected Baseline

TEST MATRIX (CONTINUED)

DSFC Response Variations - These response variations were selected to aid in defining the desirable response characteristics for the three DSFC modes (WLT, LT-I and LT-P). Another purpose of these variations was to determine more precisely the reasons for the pilots favoring one DSFC mode over another. They provided a comparison of the DSFC modes over a wide variety of control system responses, thus allowing a true evaluation of the fundamental characteristics of each particular mode.

There were four n_y response variations in the WLT mode as shown in the upper left chart. These responses ranged from extremely sluggish to quite sensitive and underdamped. Also, two n_y command prefilter variations (τ_2) were investigated for the WLT mode for the purpose of determining the allowable control system lag. These are shown in the upper middle chart.

Two sideslip response variations were investigated for the LT-P mode (lower left chart). Both were more sluggish than the baseline which produced a large n_y transient that may be unattainable when physiological or structural considerations prevail. Two n_y response variations were examined for the LT-I mode (lower middle chart). Both variations were quicker than the baseline. These two variations were introduced in Phase II to determine whether the slower tracking response of the LT-I mode was responsible for the pilots favoring the LT-P mode over this mode in Phase I.

DSFC Lateral/Directional Coupling Variations - The sideslip coupling variations were designed to determine the effect of and the allowable magnitude of sideslip coupling during a WLT. Sideslip of -4, -8, and +4 degrees per lateral G were tested (upper right chart). The n_y responses for the three sideslip coupling variations were held as close as possible to the baseline response. This was done in order to isolate the effect of sideslip coupling on the visual cues rather than the aerodynamic effect that this sideslip might have on the n_y response.

An investigation of the allowable roll during a supposedly wings level turn was completed. This was accomplished by feeding a command to the roll channel proportional to the WLT n_y command. Yaw rate to roll rate ratios (p/r) of -8, -4, 4, 8 and 12 were tested as shown in the lower right chart of the facing figure.

Roll Stabilization - A roll stabilization control system (not illustrated on the facing figure) was tested so that the wings remained level regardless of the pilot lateral stick input or gust disturbance. This control mode was switched in for the final tracking portion of the run. The purpose of this was to determine the effect of removing the lateral workload on the bombing accuracy and overall pilot rating of the DSFC configurations

Simulation Test Matrix (Continued)

- Lateral Directional Characteristics, Including Coupling Variations

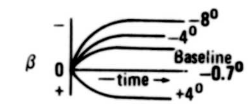
WLT, LT-P and LT-I Response Variations

All Response Variations Shown Below can be Approximated by

$$n_y/\delta = \frac{S + a}{S^2 + 2\zeta_y\omega_y S + \omega_y^2} \quad \text{where} \quad \begin{array}{ll} 1.7 \leq a \leq 3.9 & \text{(WLT)} \\ a = 0 & \text{(LT-P)} \\ a \to \infty & \text{(LT-I)} \end{array}$$

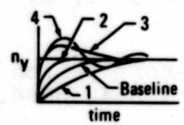
The ζ_y and ω_y variations are shown below

3 WLT Sideslip (β) Coupling Variations



Response shown for a 1 G step rudder input

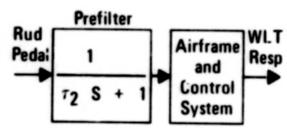
4 WLT n_y Response Variations



Response shown for a step rudder input

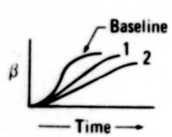
	Frequency ω_y (Rad/Sec)	Damping ζ_y
1	1.71	2.70
Baseline	2.00	1.58
2	1.80	0.96
3	3.33	0.80
4	5.84	0.30

2 Control System Prefilter Time Constant (τ_2) Variations



$\tau_{2_1} = 0.35$ Sec
$\tau_{2_2} = 0.60$ Sec
$\tau_{2_{base}} = 0.167$ Sec

2 More Sluggish LT-P β Response than Baseline and Variation in Rudder Sensitivity



Response shown for a step rudder input

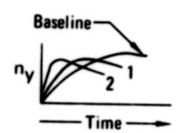
β Response

Variation	Frequency ω_y (Rad/Sec)	Damping ζ_y
Baseline	2.30	1.07
1	1.83	1.40
2	1.45	1.79

Rudder Sensitivity

Variation	Maximum β (Deg/Sec)
Baseline	11.4
Increased	16.0

Two More Rapid LT-I n_y Responses than Baseline and Variation in Rudder Sensitivity



Response shown for a step rudder input

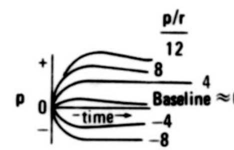
n_y Response

Variation	Frequency ω_y (Rad/Sec)	Damping ζ_y
Baseline	2.24	1.15
1	3.15	0.62
2	3.75	0.44

Rudder Sensitivity

Variation	Maximum β (Deg/Sec)
Baseline	6.1
Decreased	4.4

5 WLT Roll Rate (P) Coupling Variations



Response shown for a step rudder input

TEST MATRIX (CONTINUED)

Longitudinal Coupling - Two types of longitudinal coupling were tested during Phase II. Transient coupling and steady state coupling. The transient coupling is of the type that would occur with an n_z command longitudinal control system. The aerodynamic cross coupling from a DSFC command causes a longitudinal imbalance which, in the steady state, is compensated for by the control system. When the DSFC control is removed, a transient imbalance due to the longitudinal control system compensation occurs. The steady state coupling is of the type where a longitudinal imbalance caused by a DSFC command exists until the DSFC command is removed. A positive longitudinal coupling implies that the use of either a right or left DSFC commanded n_y (for WLT mode) or β (for the LT-P mode) results in a positive Δn_z. Conversely, a negative coupling results in a negative Δn_z for a right or left command.

For the WLT mode, transient coupling variations of $\Delta n_z/n_y$ of 1, 2, 3, and -2 were tested. Transient coupling $\Delta n_z/\beta$ for the LT-P mode were n_z/β = 0.5 and -0.5 G/deg were tested.

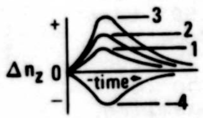
Steady state WLT longitudinal coupling $\Delta n_z/n_y$ variations tested were values of 1, 2, and -1. Values of 0.25 and 0.5 G/deg for $\Delta n_z/\beta$ were tested with the LT-P mode.

Longitudinal Damping Variations - The effects of increased and decreased short period damping on DSFC acceptability were examined. Short period damping ratios ζ_{sp} of 0.4 and 0.88 were investigated. The baseline short period damping ratio was 0.6.

Simulation Test Matrix (Continued)

- Longitudinal Characteristics, Including Coupling Variations

4 Transient Longitudinal Δn_z Coupling Variations WLT and LT-P Modes



Response shown for a step rudder input. Typical type of response for a command type of control system.

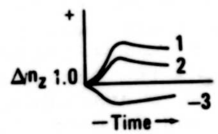
WLT

Variation	Coupling $\Delta n_z/n_y$
Baseline	0
1	3
2	2
3	1
4	–2

LT-P

Variaton	Coupling $\Delta n_z/\beta$(g's/deg)
Baseline	0.00
1	0.25
2	0.50

3 Steady State Type Longitudinal Δn_z Coupling Variations WLT and LT-P Modes



Response shown for a step rudder input. Typical type of response for a mechanical type of control system.

WLT

Variation	Coupling $\Delta n_z/n_y$
Baseline	0
1	2
2	1
3	–1

LT-P

Variation	Coupling $\Delta n_z/\beta$ (G's deg)
Baseline	0
1	0.5
3	–0.5

Increased and Decreased Short Period Damping Characteristics. Investigated with Conventional, WLT and LT-P Flight Modes.

Baseline $\zeta_{SP} = 0.60$
High $\zeta_{SP} = 0.88$
Low $\zeta_{SP} = 0.40$

TEST MATRIX (CONCLUDED)

Bomb Sights - The bomb delivery systems have been previously described. The HUD displays for the fixed (including roll stabilized) sight and the FIP sight are shown on the facing figure in the upper two charts.

Roll About the Line of Sight Control Mode - This control mode designated as RLOS, was designed to roll the aircraft about the fixed depressed reticle bomb sight line of sight, thus eliminating pendulum effect (lower left chart). There has been some speculation that the elimination of pendulum effect due to wings level turning may have been the major factor in accuracy improvement found in past DSFC tests using a fixed sight. If this is true, bombing accuracy using the RLOS mode would be nearly the same as the bombing accuracy using the WLT mode.

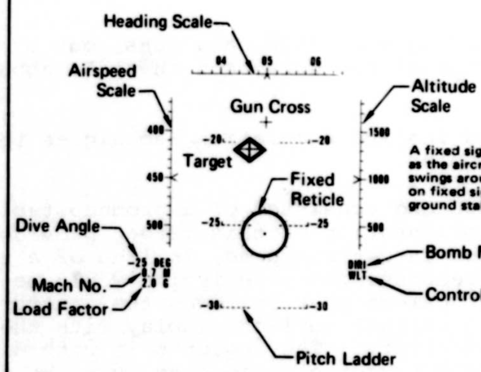
Flight Trajectory Tracking Time - The simulation task was to make a 30° dive bombing run on a ground target using the MK-82 low drag bomb. The run was started with the aircraft in trimmed flight at M = 0.8, and at an altitude and range from the target so that a 90° turn to line up with the target was required. The target was displayed on the simulator dome (shown on page 18). Both left and right turns to the target were programmed. After the run commenced, the pilot rolled into a turn towards the target and let the nose drop to the required dive angle. Approximately 12 seconds were available, after roll out for the baseline trajectory, to acquire the target, track it, and drop the bomb. Tracking time (time from roll out to bombs release) was varied to determine if this parameter had any effect on the pilot opinion or on the bombing accuracies of the various configurations (none were evident). The values used are shown in the lower, middle chart. Note, this relatively long tracking time was selected as a compromise between combat maneuver realism and providing sufficient time to feel out the aircraft.

Pilot Workload Runs - These runs were performed in straight and level flight with the target at a constant range of 5,000 feet and initially at the same altitude as the aircraft as depicted in the lower right chart. The various aircraft configurations were flown in smooth air with the target moving randomly vertically and/or horizontally. Two aiming pippers were employed. One was fixed to the aircraft at the initial trimmed aircraft velocity vector point. The other pipper was centered about the aircraft velocity vector. The first pipper is representative of a fixed bomb sight and will show the aircraft short period motions as perturbed by the pilot. The second pipper is representative of an advanced bomb sight since short period types of aircraft motions do not show up on the sight.

Simultation Test Matrix (Concluded)

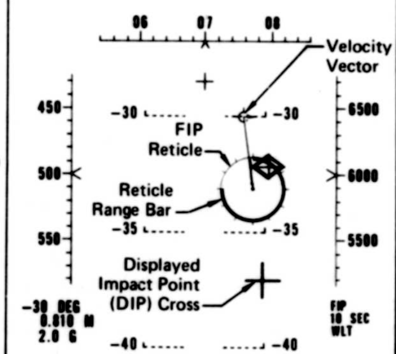
- Bomb Sights

Fixed and Fixed Roll Stabilized Sight Head Up Display (HUD) Symbology



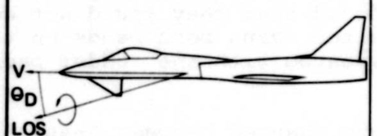
A fixed sight remains in the center of the HUD as the aircraft rolls. A fixed sight roll stabilized swings around the velocity vector (not displayed on fixed sight HUD) to essentially remain ground stabilized.

FIP Sight Hud Symbology



- Miscellaneous

Roll About the Fixed Bomb Sight Line of Sight (RLOS) Control Mode



This control mode eliminates the fixed sight pendulum effect by rolling the aircraft about the bomb sight line of sight.

Flight Trajectory Tracking Time

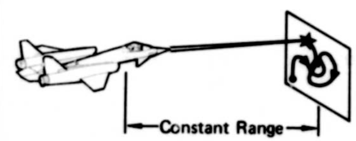
The simulation was set up so that a 90 degree turn while dropping the nose to the dive angle was needed to acquire the target. The initial conditions were varied to investigate tracking time on bombing accuracy.

Initial Conditions

Altitude Ft.	Mach	Range	Approximately Tracking Time Sec.
10,000	0.8	17,000	12 (Baseline)
9,000	0.8	15,000	9
11,500	0.8	20,000	16

Pilot Workload Runs

A group of separate runs were set up to investigate closed loop (pilot in the loop) characteristics. These consisted of the pilot tracking a vertically, horizontally or combined motion moving target at a constant range.



SIMULATION TEST

The simulation test was conducted in the MCAIR fixed base simulator designated as MACS I (Manned Air Combat Simulator I), and consists of a fully instrumented, single-place, fighter-type cockpit centered inside a spherical dome. A projection system provides for the display of the horizon and ground target scene. A sketch of the MACS I simulator is shown on the facing page.

The simulation was conducted in two phases covering over 2500 data runs, out of which 2459 were analyzed. Phase I simulation lasted about one week, and Phase II about two weeks.

The Phase I simulation uncovered several procedures and simulation techniques that were unsatisfactory from a piloting or analysis viewpoint.

The dive bombing target was displayed on the HUD and consisted of a ground stabilized diamond shaped target. The apparent size and orientation of this target provided attitude and range cues to the pilot. A HUD displayed target was used, in lieu of a target painted on a terrain map, to assure that no adverse response characteristics would be introduced into the simulation by the translating TV camera that followed the aircraft trajectory over the terrain map. Phase I used only a virtual horizon display with the HUD target and the pilots did not feel this was satisfactory. They equated it with dive bombing a marker flare at night. Phase II used the HUD target superimposed over the closed circuit TV displayed terrain map to provide a realistic background terrain view.

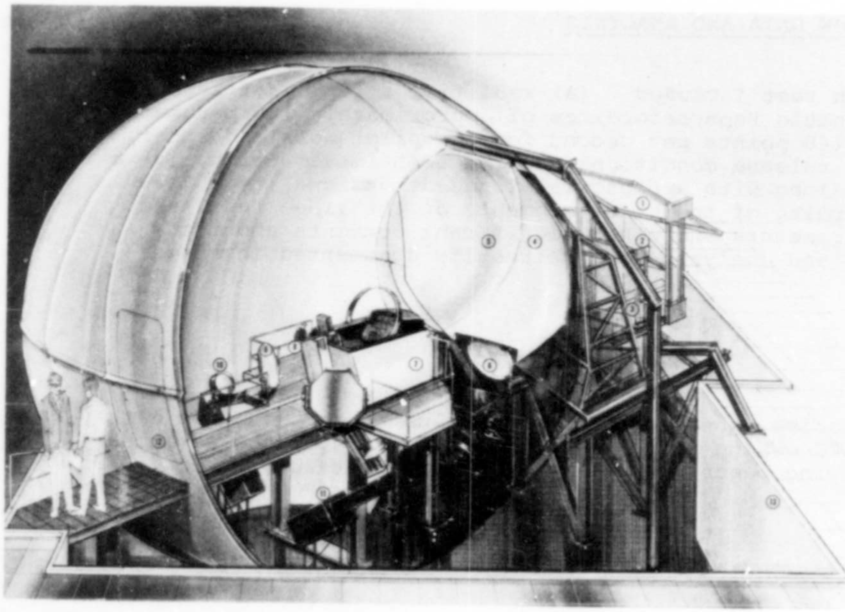
Phase I employed Dryden gusts, discrete gusts and a wind shear during the dive bombing pass. Pilots felt that the Dryden gusts were unrealistic for the task. Also, analysis of the data showed that the Dryden gusts were masking some of the aircraft characteristics that were being investigated. For Phase II, the Dryden gusts were eliminated.

It was initially decided that the lateral translation control would be implemented by an isometric thumb button on the control stick. Pilots found that they could not control both the lateral translation and drop the bomb, and started using both hands on the stick. To alleviate this, the lateral translation was implemented with the rudder pedals for Phase II.

Several other features that improved the simulation were changed between Phases I and II. Pilot workload runs were accomplished in Phase I using the Dryden gusts as the disturbing function; in Phase II they were obtained by having the pilots track a random moving target. Also, during Phase II, the pilots spent a longer session in the simulator at any one time which allowed the pilots more continuity.

Simulation Layout

Manned Air Combat Simulator



Legend

1 Virtual Horizon Mirror
2 Rear Projection Screen (Virtual Horizon)
3 Horizon Projection
4 Spherical Mirror
5 Beam Splitter
6 Virtual Display Optics
7 Crew Station
8 Real Horizon Projector
9 Real Target Mirrors
10 Focus Lenses (Real Target)
11 Real Target Projection
12 Entrance to Spherical Enclosure
13 Pit Area

Phase I Simulation Critique

Critique:

Virtual horizon display used in Phase I unsatisfactory.

Remedy:

A translating terrain map display that came into view about half way through the roll in turn employed. A virtual cloud cover horizon display was used for initial portion of turn.

Critique:

Dryden gust spectrum unrealistic for the dive bombing task.

Remedy:

Dryden gusts eliminated for Phase II. Retained the discrete gusts, randomly applied, and wind shear.

Critique:

Isometric thumb button as the lateral translation controller not satisfactory. Two hands required on stick to control and drop bomb.

Remedy:

Lateral translation accomplished with rudder pedals in Phase II

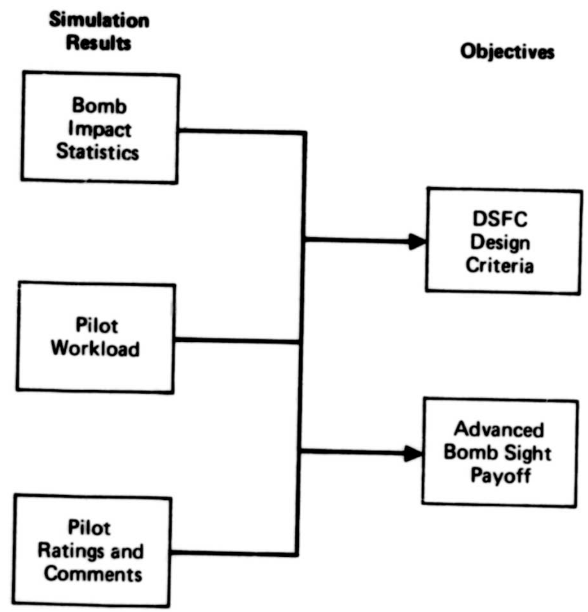
SIMULATION DATA AND ANALYSIS

Data gathered during the simulation test included: (a) real time strip chart recording of approximately 40 parameters, (b) magnetic tape recordings of approximately 100 parameters at a data rate of 20 points per second (40 points per second for the pilot workload runs), (c) magnetic tape recording of the bomb release conditions and the bomb impact point, (d) a video tape of the view through the HUD along with a pictorial three-dimensional type view of the bombing run trajectory, (e) recording of the pilot comments on the video tape, and (f) manual log listing pertinent run parameters and other significant comments about the run. All these data have been compiled and analyzed and the results documented in three categories:

(1) Bomb impact statistics
(2) Pilot workload results
(3) Pilot ratings and comments

The results from these three categories, when combined and evaluated, provide the data and rationale for the development of DSFC design criteria and establishment of the advanced bomb sight payoff with DSFC. The following pages present these pertinent results.

Simulation Results Established DSFC Design Criteria and Identified Advanced Bomb Sight Payoff



BOMB IMPACT STATISTICS

Each of the four pilots made at least five dive bombing passes per configuration, and as many as 15 for each baseline configuration in three groups of five each corresponding to early, mid, or late in the simulation. This provided a minimum of 20 and a maximum of 60 bomb impacts per configuration for use in the statistical evaluation.

Baseline Configurations with Fixed Sight - The statistical method employed in fixed sight data analysis consisted of mean, variance, and standard deviation estimates of the elevation and azimuth bomb release aiming errors corresponding to the downrange and crossrange bomb impact miss distance respectively. The bomb impact circular error probable (CEP) was computed from the standard deviations according to the equation CEP = 0.5887 $(\sigma_\theta + \sigma_\psi)$ where σ_θ and σ_ψ are the elevation and azimuth standard deviation aiming errors, respectively.

The upper left chart of the facing figure shows the fixed sight CEP results of the baseline configurations along with the roll stabilized sight and the RLOS flight mode. These results show that eliminating the pendulum effect of the fixed sight by roll stabilizing the sight, rolling about the line of sight, or performing a wings level turn, substantially reduce the CEP. Also evident is that the LT-I mode is unsuited for dive bombing with a fixed sight.

Baseline Configurations with FIP Sight - The advanced bomb sight (FIP) statistical data analysis employed the analysis of variance techniques using a fixed effects model and hypothesis testing using the F test as the criterion for acceptance or rejection. Volume II of this report presents the complete theory and results; this volume presents only the CEP results of several of the configuration groups simulated.

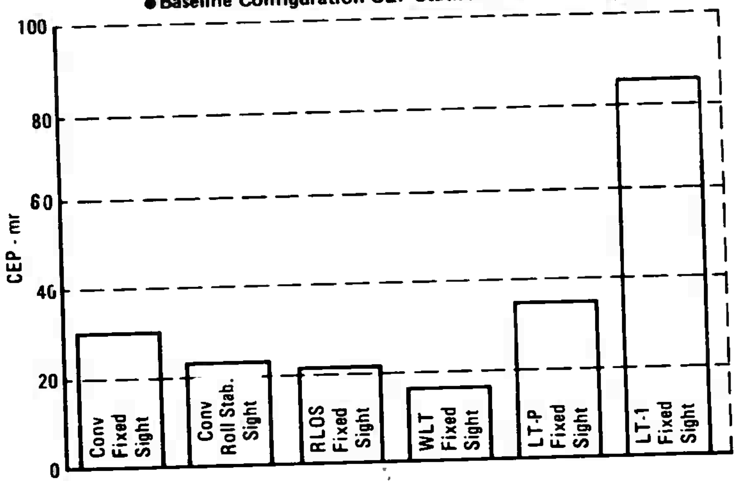
The lower left chart shows the CEP's for the baseline configurations. It is evident that the three DSFC modes (WLT, LT-P and LT-I) have lower CEP's than the conventional aircraft. Note that the CEP's follow the same order as the pilot ratings presented on page 28. It is left to the reader to decide if this 1 milliradian improvement is beneficial.

WLT Variations with FIP Sight - The upper right chart shows the WLT $\Delta n_z/n_y$ coupling effect on CEP, and indicates clearly the detrimental effect of this coupling. Note; the baseline WLT CEP's are different between the charts since only the group of five baseline runs per pilot that corresponded to the time frame (early, mid or late simulation) of the other runs were used.

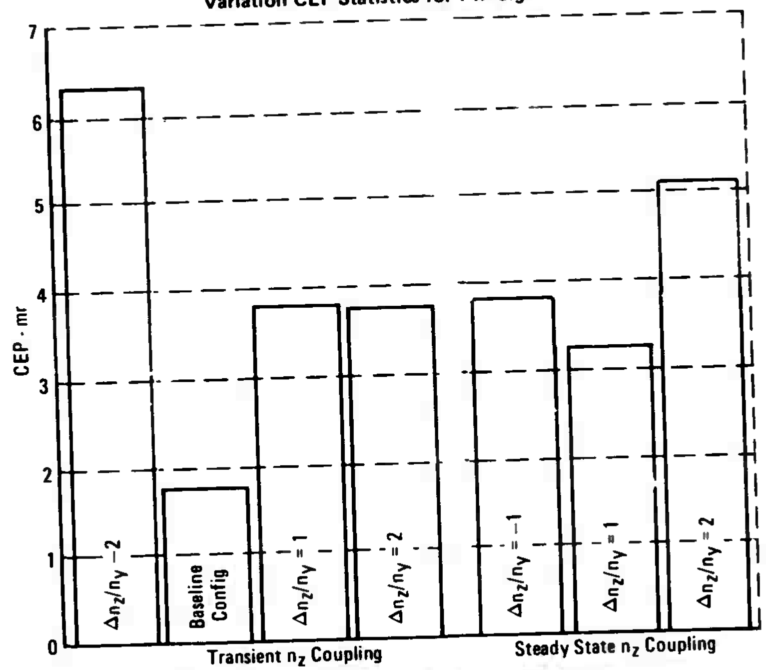
The lower right chart shows the effect of sideslip coupling. Negative sideslip coupling had a greater detrimental effect than positive coupling which is again consistent with the pilot ratings shown on page 32.

Bomb Impact Statistics

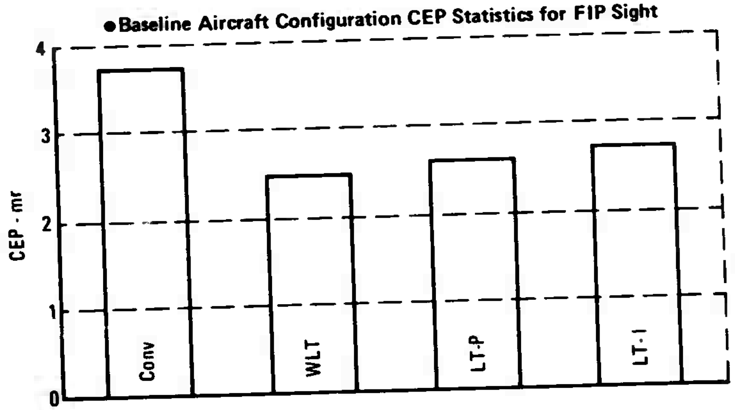
●Baseline Configuration CEP Statistics for Fixed Sight



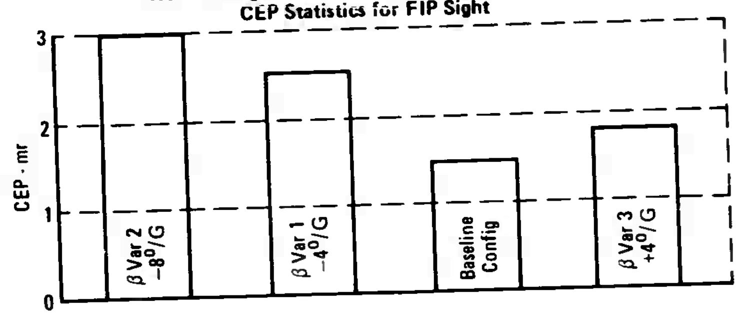
●WLT Configuration Transient and Steady State n_z Coupling Variation CEP Statistics for FIP Sight



●Baseline Aircraft Configuration CEP Statistics for FIP Sight



●WLT Configuration Sideslip Response Variation CEP Statistics for FIP Sight



BOMB IMPACT STATISTICS (CONCLUDED)

WLT Variations with FIP Sight (Continued) - The WLT n_y response variations effect on CEP is shown in the upper left chart. As previously described on page 11, the responses ranged from very sluggish, n_y Var. 1, to highly responsive and underdamped, n_y Var. 4. The baseline response was between Var. 1 and 2. There was little effect on CEP. The results were consistant with the pilot ratings and comments (see page 30) which indicated very little difference in their acceptability to the pilots.

Roll rate coupling effect on CEP for the WLT flight mode is shown in the lower left chart. Pilot comments indicated they did not mind a positive roll coupling but objected strongly to any negative roll coupling (see page 32). The CEP's did not reflect this impression. The roll coupling $p/r = -8$ had the worst CEP of the roll coupling cases, however, $p/r = -4$ had the best. Roll coupling for WLT should probably be avoided, however, a small positive value could probably be tolerated without affecting the CEP or encountering adverse pilot comments.

Composite System Error Budget and CEP - The primary focus of this study was the investigation of aiming errors due to interactions between the pilot and aircraft configuration. The statistical analyses results shown characterized these errors under the assumption that there were no aircraft system or bomb ballistic errors. Also, it was assumed that the bomb was released from the aircraft center of gravity which ignored the effect of errors caused by body rate induced released velocity increments at weapon store locations other than the aircraft C.G.

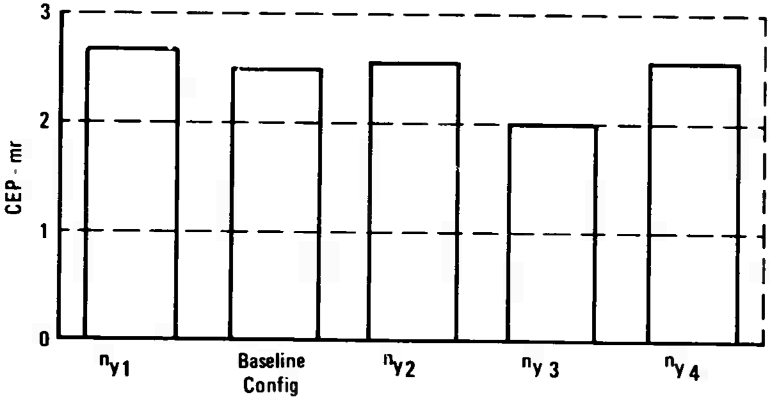
The purpose of the right hand chart is to summarize these additional error sources. These errors are divided into two classes viz; those over which the pilot possesses control and those which he does not. This summary is restricted to the FIP bomb sight, therefore, errors due to not meeting prescribed release conditions of a fixed sight are not considered.

The errors due to effects over which the pilot has no control are system errors involving measurement accuracies, alignment accuracies and bomb dispersion due to ballistic sources. The CEP sub-total of these errors is shown. The errors over which the pilot has some control are the aircraft body rate induced velocity errors and aerodynamic errors due to the existance of a sideslip at the time of bomb release. The aircraft body rate induced errors were computed using the standard deviation of the rates existing at bomb release. A bomb store location 10 ft. lateral from the C.G. was assumed. The aerodynamic effects on the bomb due to the presence of a sideslip angle at release were obtained by using the MK-82 bomb characteristics in conjunction with the simulation data.

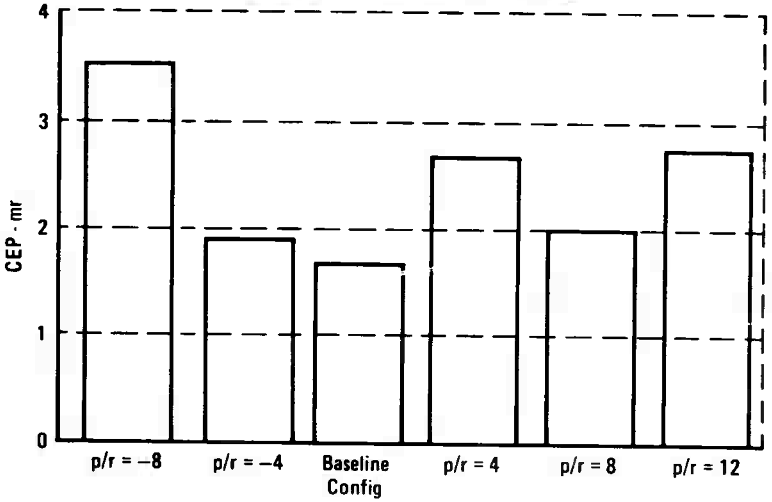
The results of statistically adding all these errors with the aiming error obtained from the simulation are shown as a composite CEP. WLT shows about a 15% improvement over the conventional mode using an advanced sight.

Bomb Impact Statistics (Concluded)

- WLT Configuration Lateral Acceleration Response Variation CEP Statistics for FIP Sight



- WLT Configuration Roll Rate Coupling Response Variation CEP Statistics for FIP Sight



- Composite System and Aiming Errors

Error Source	Configuration							
	Conventional		WLT		LT-P		LT-I	
	AZ (mr)	EL (mr)	AZ (mr)	EL (mr)	AZ (mr)	EL (mr)	AZ (mr)	EL (mr)
Radar Slant Range Measurement	–	0.3	–	0.3	–	0.3	–	0.3
Elevation Angle References	–	1.8	–	1.8	–	1.8	–	1.8
Radar Beam Elevation Position	–	1.25	–	1.25	–	1.25	–	1.25
HUD Reticle Position	1.2	1.5	1.2	1.5	1.2	1.5	1.2	1.5
Ground Speed Measurement	2.2	1.3	2.2	1.3	2.2	1.3	2.2	1.3
Vertical Velocity Measurement	–	1.2	–	1.2	–	1.2	–	1.2
Ejection Velocity	–	0.9	–	0.9	–	0.9	–	0.9
Release Time Delay	–	0.0	–	0.0	–	0.0	–	0.0
Sideslip Measurement Error Contribution	0.03	–	0.03	–	0.03	–	0.03	–
Ballistic Dispersion	2	2	2	2	2	2	2	2
Ballistic FIP Computation	–	0.3	–	0.3	–	0.3	–	0.3
Azimuth Reference Boresight	0.2	–	0.2	–	0.2	–	0.2	–
System Errors CEP (mr)	4.2		4.2		4.2		4.2	
Body Rate Induced Error	–	0.1	–	0.09	–	0.06	–	0.06
Sideslip Induced Error	0.0	–	0.0	–	0.6	–	0.6	–
Pilot Aiming Error	3.0	3.5	2.1	2.2	1.8	2.6	2.6	2.2
Composite CEP (mr)	5.7		4.9		5.0		5.1	

PILOT WORKLOAD INVESTIGATION

A series of pilot workload runs were completed and consisted of the pilot tracking a moving target for one minute. The target motion was generated by 15 sine waves spanning a frequency range from 0.21 to π radians per second, and having an rms motion, as viewed through the HUD, of 12.5 milliradians. These pilot workload runs were completed to provide an insight of why the pilots rated the various configurations.

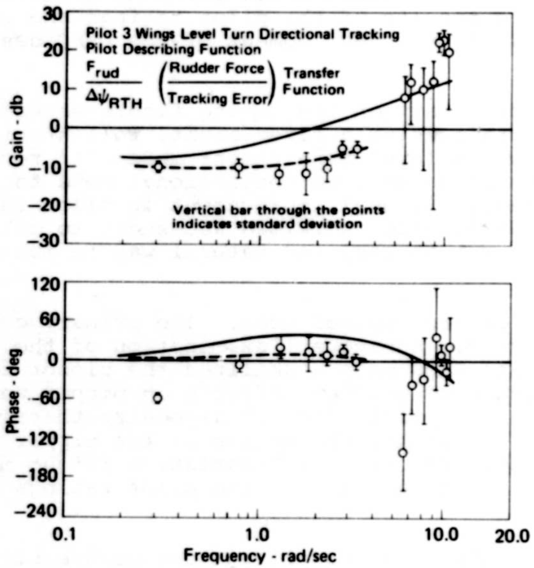
The pilot describing functions were obtained using a fast Fourier transform program and they were then fit with a quasi-linear pilot model transfer function of the form shown in the left chart on the facing figure. The two fits of the data using low frequency data points only (dashed line) and all points (solid line) indicate that this pilot model does not fit the rudder pedal control pilot describing function obtained from this test.

An interesting result was obtained when comparing the rms tracking error of the three DSFC modes. This showed that LT-P mode had the least tracking error (upper right chart). This mode is mechanized so that a deflection of the rudder pedal will result in a sideslip angle β proportional to the rudder pedal deflection. This type of tracking has a direct relationship between control movement and the display movement which it produces and is a zero order task. A WLT tracking with either a fixed or velocity sight and LT-I mode tracking with a velocity sight are first order tracking tasks and can be represented by an integrator in the tracking system that inserts a phase lag of 90 deg in the pilots response. The higher the order of the tracking task, the harder it is for the pilot to accurately track. The results of this analysis show it may be advisable to incorporate a LT-P mode mechanization for the WLT mode since the pilots like that mode the best, it would be applicable to both fixed and velocity sights, and be usable for both gunnery and bombing. This suggests implementing a WLT mode that would provide a flight path angle turn, at zero β, proportional to the rudder pedal deflection. This would provide for a faster turn to a new direction and may be beneficial in the quick acquisition and designation of a target for the various bombing and gunnery tasks.

Another interesting result was that pilots can adapt, without experiencing an appreciable degradation of their capability or an increase in their workload, to a large variation of DSFC response characteristics. The bottom right chart shows the pilot rms tracking error and rudder pedal force obtained from the workload runs, and the pilot ratings and bomb impact CEP obtained from the dive bombing runs for the large range of WLT response characteristics. The results are ordered according to increasing responsiveness, from n_{y1}, very sluggish, to n_{y4}, very responsive and lightly damped. There is no trend evident and these results, when combined with those of the other pilots, imply that rudder pedal control is an insensitive device and that pilots can easily adapt to a large range of control responses.

Pilot Workload Results

- **Quasi-Linear Pilot Model Does Not Fit Rudder Pedal Tracking Very Well.**

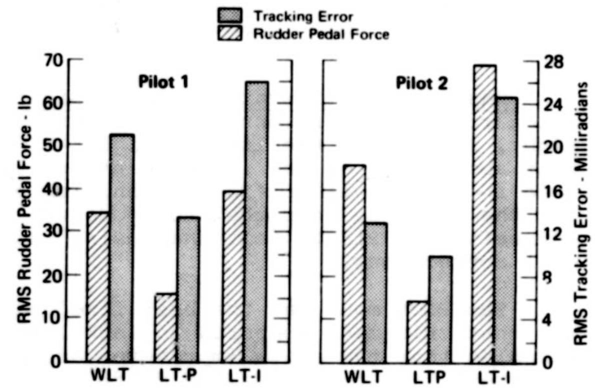


Quasi-Linear Pilot Model

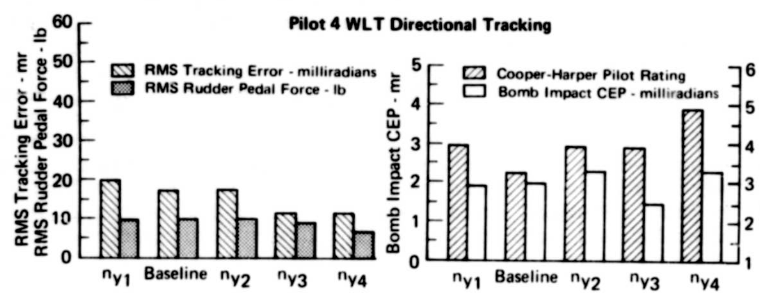
$$K_p \frac{T_1 S + 1}{T_2 S + 1} e^{-\tau s}$$

- - - - Fit to π rad/sec
—— Fit to 10 rad/sec

- **Lateral Translation Proportional Mode Produces The Least Tracking Error**



- **Pilots Can Adapt To a Large Range of Response Characteristics Using The Rudder Pedal For DSFC**



PILOT RATINGS AND COMMENTS

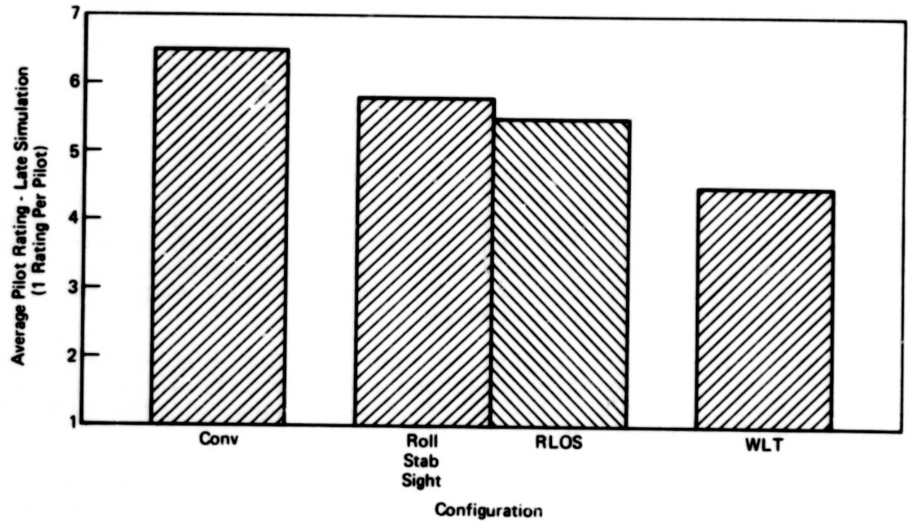
Four pilots, two military and two MCAIR test pilots participated in the simulation. Pilots were required to rate each configuration after five dive bombing passes. The Cooper-Harper rating scale was used but no half ratings were allowed. Pilot comments given during the simulation were recorded on magnetic tape. The results of the pilot ratings and comments along with the bomb impact scores formed the basis for the development of the DSFC design criteria shown later.

Baseline Configurations Fixed Sight - The upper chart on the facing figure shows the pilot rating comparisons for the conventional aircraft using a fixed sight, roll stabilized sight, roll about the line of sight (RLOS) and a wings level turn flight mode. It reveals that about half of the improvement in pilot rating in going from conventional mode to the WLT mode is due to elimination of pendulum effect. The additional improvement in pilot rating for the WLT mode over the RLOS mode was due to reduced pilot workload necessary to make fine corrections. Pilots felt that using rudder pedals was an easy and natural way to make lateral corrections.

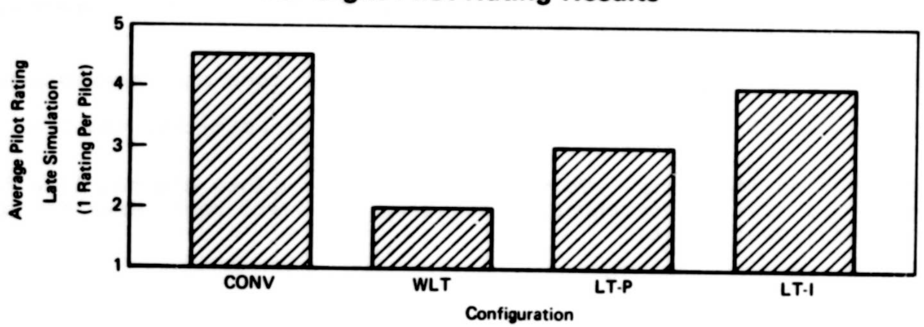
The RLOS mode was the best fixed sight roll-to-turn control mode. The primary complaint was that this mode appeared to lack lateral authority. Subsequent examination of the data revealed that the above impression arose because the RLOS mode stabilized the pipper to such an extent that the crosswind drift effects and crosswind gradient effects on pipper movement (or lack of movement) were discernable even though the pilots did not recognize these effects as such. With the conventional flight mode and fixed sight, the motion of the pipper due to pendulum effect obscured the crosswind drift effect. The lateral translation flight modes were of no practical use for fixed sight bombing. (See page 37 for the pilot ratings and further discussion.)

Baseline Configurations FIP Sight - The FIP sight made the pilots task much easier and resulted in better pilot ratings (lower chart). The primary complaint about the conventional mode was that rolling to turn is a difficult method for making small corrections. The baseline WLT configuration was the overall favorite of the pilots. No significant complaints were expressed about any aspect of that configuration. Pilots also liked the LT-P mode for dive bombing with the FIP sight although not as much as the WLT mode. The primary complaint of the LT-P mode was that a continuous rudder pedal force was necessary to maintain the correction. Whatever pedal force was used to correct the initial error became the position about which all further incremental corrections were made. The LT-I mode was not liked as much as the WLT mode by any of the pilots. Pilots 1 and 4 preferred the proportional mode to the integral mode. Pilots 1 and 2 commented on LT-I model sensitivity and pilot 4 stated that he had difficulty with pipper positioning.

Fixed Sight Pilot Rating Results



FIP Sight Pilot Rating Results



WLT Lateral Acceleration Response Variations, FIP Sight - The FIP sight tracking problem is primarily related to the response of the velocity vector to rudder pedal inputs. Azimuth error between pipper and target is identical to the azimuth error between the velocity vector and the target. Since the rate of change of the velocity vector azimuth angle is directly related to lateral acceleration n_y, variations of this response parameter were explored.

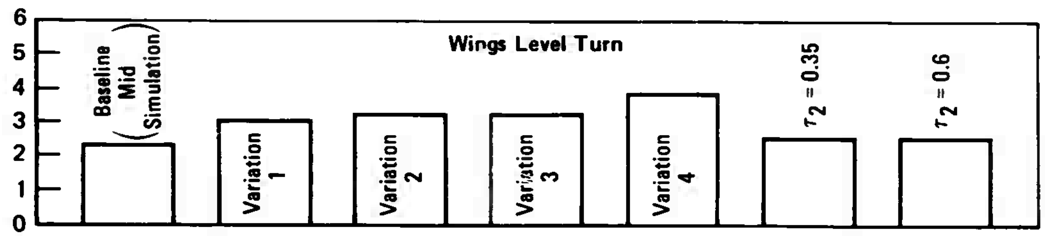
A low order equivalent system of the form $\frac{n_y}{\delta} = K \frac{s + a}{s^2 + \zeta_y \omega_y s + \omega_y^2}$ was used to approximate the high order n_y response variations. This was accomplished by a curve fitting program which varied the parameters a, ζ_y, ω_y, and K to match as closely as possible the Bode plots of gain and phase for high order system. Based on the low order system, the natural frequency of the n_y responses ranged from 1.07 to 5.84 and the damping ratio ranged from 0.3 to 2.70 as shown on page 12. The only configuration that received significantly adverse comments was variation 4, (upper chart of facing figure). This configuration was also the only one that Pilot 4 detected as being different from baseline.

The conclusion drawn from these results is that the pilots are relatively insensitive to variations in WLT lateral acceleration response characteristics. This conclusion is consistent with the results from the pilot workload runs (page 26) and further verifies that rudder pedal control is an insensitive controller.

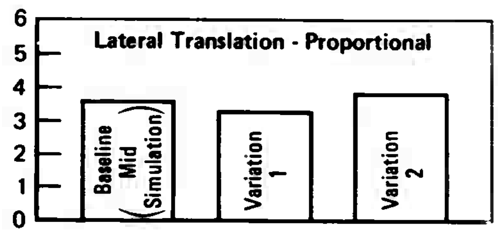
LT-P Response Variations, FIP Sight - The baseline LT-P mode produced large n_y spikes during rapid control inputs. This could possibly be unacceptable in an actual aircraft both in terms of pilot, physiological effects, and control surface loads. The purpose of this investigation was to determine whether response characteristics with a lower peak n_y would be acceptable for dive bombing tracking. The n_y response Bode plots were matched with a low order equivalent system as described above for the WLT variations. The frequency and damping ratio values used are shown on page 12. No great differences were detected by the pilots between these characteristics (middle chart).

LT-I Response Variations, FIP Sight - The LT-I flight mode characteristics fit a low order equivalent system of the form $\frac{n_y}{\delta} = \frac{K}{s^2 + 2\zeta_y \omega_y s + \omega_y^2}$. Note that the LT-I low order equivalent system has no lead term. This may explain why pilots did not like it as much as WLT or LT-P modes. No great differences of pilot opinion were registered for any of the LT-I variations simulated (lower chart).

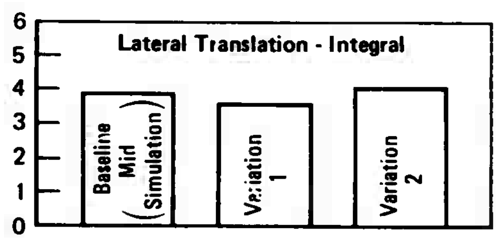
FIP Sight Pilot Rating Results - DSFC Response Variations



- No Significant Variation In Pilot Opinion Except Possibly For Variation 4 Which Was The Low Damping Ratio Variation (Note That The Prefilter, τ_2 Variations Are Considered To Be Response Variations



- No Significant Variation In Pilot Opinion For Any LT-P Response Variation



- No Significant Variation In Pilot Opinion For Any LT-I Response Variation

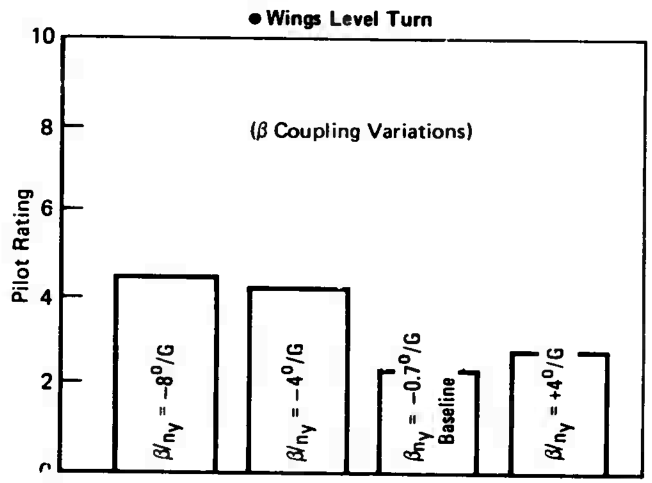
WLT Sideslip (β) Coupling, FIP Sight - For the WLT mode with zero or small sideslip coupling, the pipper remains essentially fixed on the HUD and the target moves across the HUD as the aircraft turns in response to rudder pedal commands. With the lateral translation modes, the target remains relatively fixed in the HUD while the pipper, being tied to the velocity vector, moves across the HUD in response to rudder pedal commands. Either case is easily interpreted by the pilot. When sideslip is developed in the WLT mode, the pipper moves with the velocity vector across the HUD in direct proportion to the sideslip angle being developed while the target moves (relative to the HUD) in direct proportion to the azimuth angle change of the aircraft. The n_y response characteristics of the baseline and each of the variations simulated were identical allowing only the effects of sideslip on the visual cues to be investigated.

Only Pilots 1 and 3 noticed the -4 degrees per G sideslip coupling. Pilot 1 strongly disliked it and his remarks indicate that he interpreted the sideslip to be positive rather than negative. This misinterpretation was most likely due to the illusion with negative sideslip coupling, that the pipper initially appeared to move in a direction opposite that commanded. The -8 degree per G coupling evoked similar comments. Pilot 2 noticed this coupling and his remarks indicate that the visual effects described above bothered him but only for large control inputs.

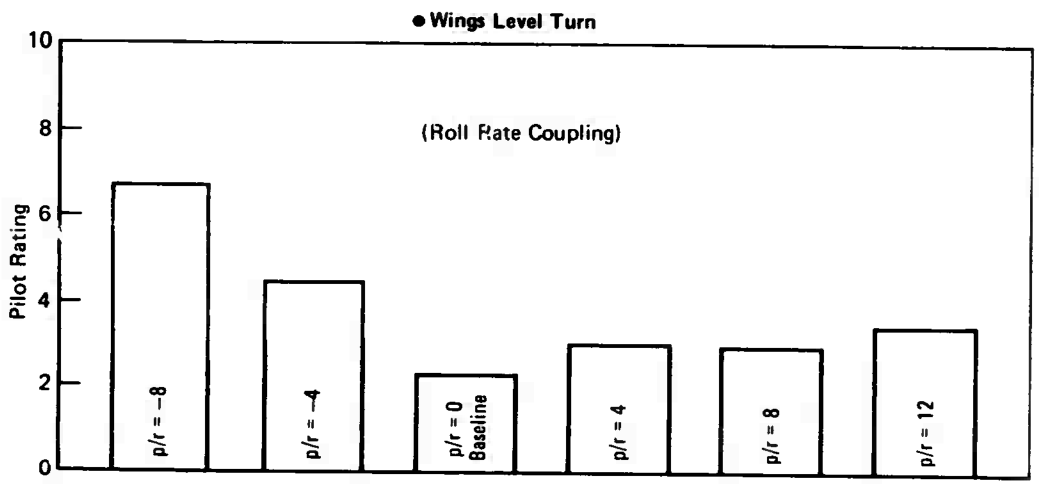
The +4 degrees per G case evoked little adverse comment. For FIP sight WLT bombing therefore, an initial yaw opposite to that commanded (positive sideslip) is preferable to too much initial yaw in the direction commanded (negative sideslip). The upper chart of the facing figure shows the average pilot rating results for the WLT sideslip coupling.

WLT Roll Coupling, FIP Sight - The pilots generally did not mind positive roll coupling as high as 8 deg/sec per deg/sec of yaw rate. They felt this was natural dihedral effect. Even a p/r (roll rate/yaw rate) of 12 was rated good by 2 of the pilots. Negative p/r coupling was, however, strongly disliked by pilots 1 and 2 although pilot 2 apparently did not notice the p/r = -4 coupling. They felt this was an unnatural aircraft characteristic and could be dangerous in certain flight situations. The lower chart shows the pilot rating variation with roll coupling.

FIP Sight Pilot Rating Results - Lateral/Directional DSFC Coupling



- Pilots Objected to Negative Sideslip Coupling of −4°/G and Above
- No Objections to Positive Sideslip Coupling



- Pilots Objected to Negative Roll Coupling
- No Objections to Positive Roll Coupling

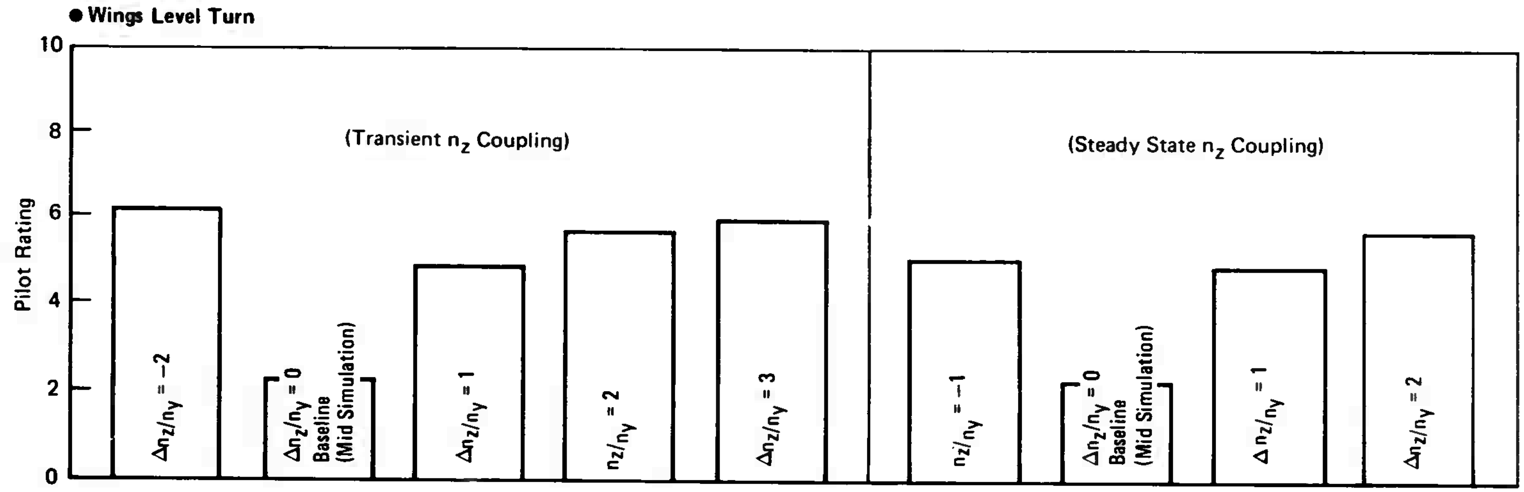
PILOT RATINGS AND COMMENTS (CONTINUED)

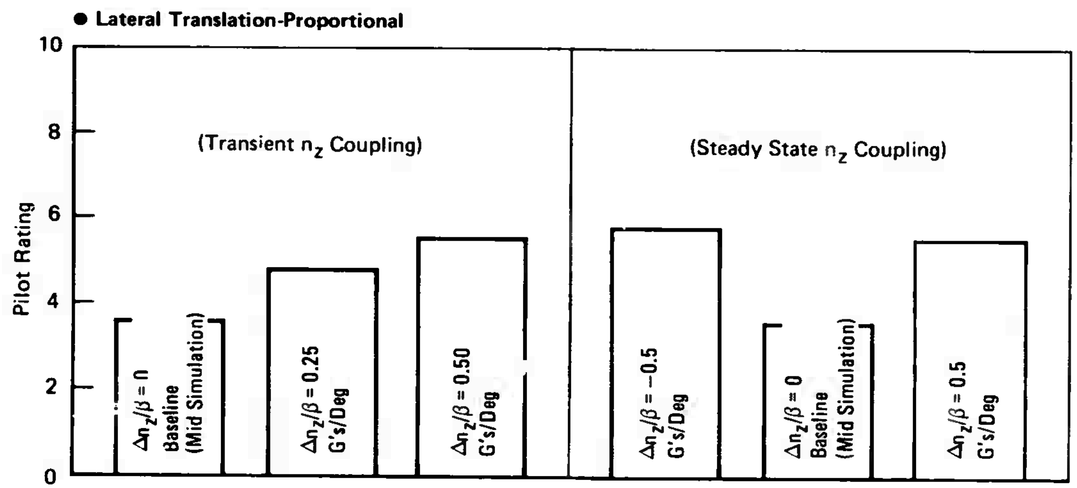
WLT Longitudinal (Δn_z) Coupling, FIP Sight - Two types of longitudinal coupling were examined, transient coupling and steady state coupling. The transient coupling is of the type that would be experienced with a longitudinal n_z command system. The aerodynamic cross coupling from a DSFC command causes a longitudinal imbalance which, in the steady state, is compensated for by the longitudinal control system. When the DSFC command is removed a transient imbalance due to the longitudinal control system compensation occurs. The steady state coupling is of the type where a longitudinal imbalance caused by a DSFC command exists until the command is removed.

Steady state coupling was rated as being slightly worse than transient coupling. Pilots found they could ignore the longitudinal oscillation of the transient type, but they actually had to apply a control force for compensating the steady state coupling. One G per G transient coupling WLT was given a worse rating than the conventional mode by 2 of the pilots and a better rating by the other two. Pilots 2 and 4 objected least to the coupling, at least for the 1 and 2 G's per G coupling. The upper chart of the facing figure shows the pilot rating results for the longitudinal coupling variations discussed above. Note that for a good WLT flight mode, no longitudinal coupling should be present.

LT-P Longitudinal (Δn_z) Coupling, FIP Sight - Both transient and steady state coupling variations, similar to those looked at with the WLT mode, were investigated for the LT-P mode. The least coupling, 0.25 G/deg, was rated as annoying but tolerable by the pilots. Higher coupling values were essentially unacceptable for the task. The lower chart shows the average pilot ratings vs coupling values for the LT-P mode.

FIP Sight Pilot Rating Results - Longitudinal DSFC Coupling





- Pilots Objected to Lowest Level of Coupling Tested on Both the WLT and LT-P Modes

PILOT RATINGS AND COMMENTS (CONTINUED)

Conventional Flight Mode Short Period Damping Ratio Variations - All pilots mentioned at one time or other that the longitudinal short period mode may be too sensitive or have slightly less damping than optimum. Short period damping ratio, ζ_{sp}, was 0.60 and $\omega_n^2/n/\alpha$ was 0.35. The steady state stick force gradient was 4.25 lb/G. All are within level 1 boundaries. Apparently, for the dive bombing task, a highly damped response is desirable.

Generally, when ζ_{sp} was increased to 0.89, Pilot 2 still felt that damping should be increased more and Pilots 3 and 4 did not notice the increase. All pilots noticed when damping was lowered to 0.40. Pilots 1 and 2 did not like the lower damping and Pilots 3 and 4 did not mind it.

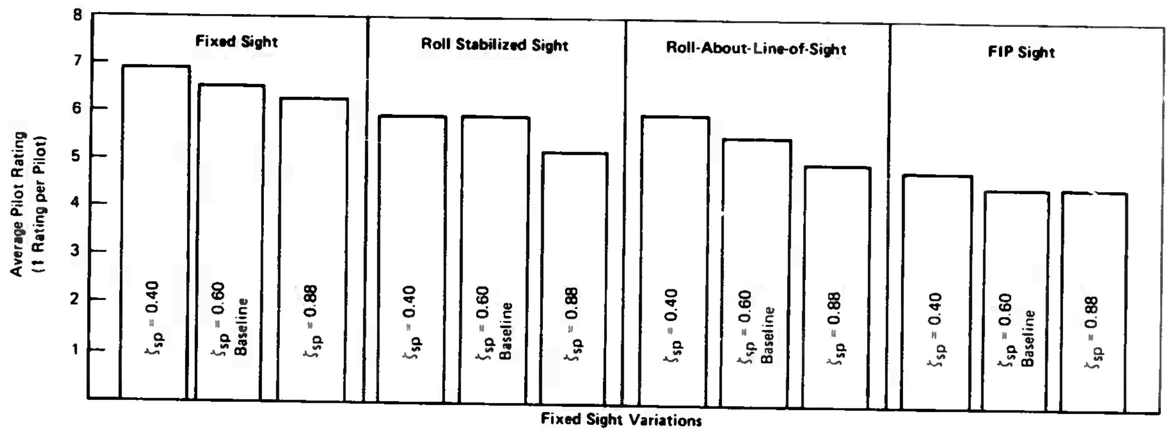
The results of changing the short period damping ratio on the conventional flight mode are shown in the upper chart of the facing figure. The fixed sight results, which includes the roll stabilized sight and the roll about the line of sight, show that increasing the damping ratio had a beneficial effect on the pilot ratings. For the FIP sight, increasing the damping ratio had no effect on pilot rating. Decreasing the damping ratio always had an adverse effect on pilot rating. Similar results (not shown) were obtained for the other flight modes (WLT and LT-P) although the pilot ratings were not quite as critical on the lowering of the damping ratio. This indicates that slightly lower longitudinal short period damping could be tolerated when using WLT or LT-P for the bombing task than when using the conventional flight mode.

DSFC Roll Stabilization - Pilot 4 liked the roll stabilization for WLT although not enough to change his pilot rating from the baseline WLT. Pilot 1 rated the roll stabilized WLT mode better than baseline, but Pilots 2 and 3 rated it worse. These two pilots disliked being deprived of this degree of freedom even though it was explained that roll stabilization could be implemented to feel like an increased stick breakout force, i.e., pilots would regain roll control when lateral stick force exceeded a specified amount. Roll stabilization for the lateral translation modes produced less criticism than for WLT. The pilot ratings are shown in the lower chart.

One fact brought out was that roll stabilization for LT-P mode could be a hindrance if large corrections had to be made after switching it on. Since the maximum angular correction possible with LT-P control was 11.4° at 117 lb rudder force, maintaining a large correction could be tiresome since holding a continued rudder force is required.

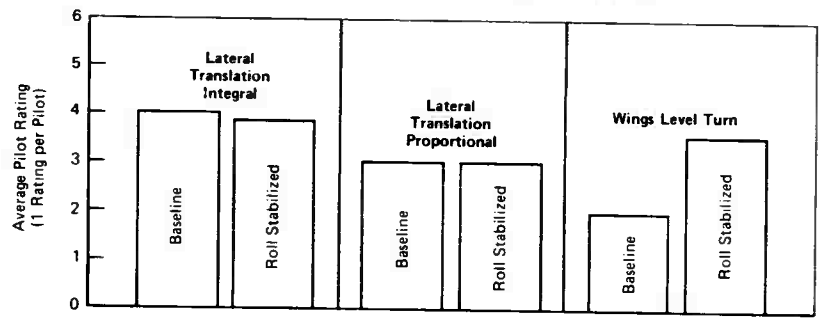
Conventional Flight Mode Short Period Damping Ratio Variations

- Fixed Sight: Pilots liked increased damping ratio and disliked decreased damping ratio
- FIP Sight: Increased damping ratio had negligible effect on pilot opinion. Pilots disliked decreased damping ratio.



DSFC Roll Stabilization

- Roll Stabilization Effects on Pilot Opinion Range From Negligible to Adverse



PILOT RATINGS AND COMMENTS (CONCLUDED)

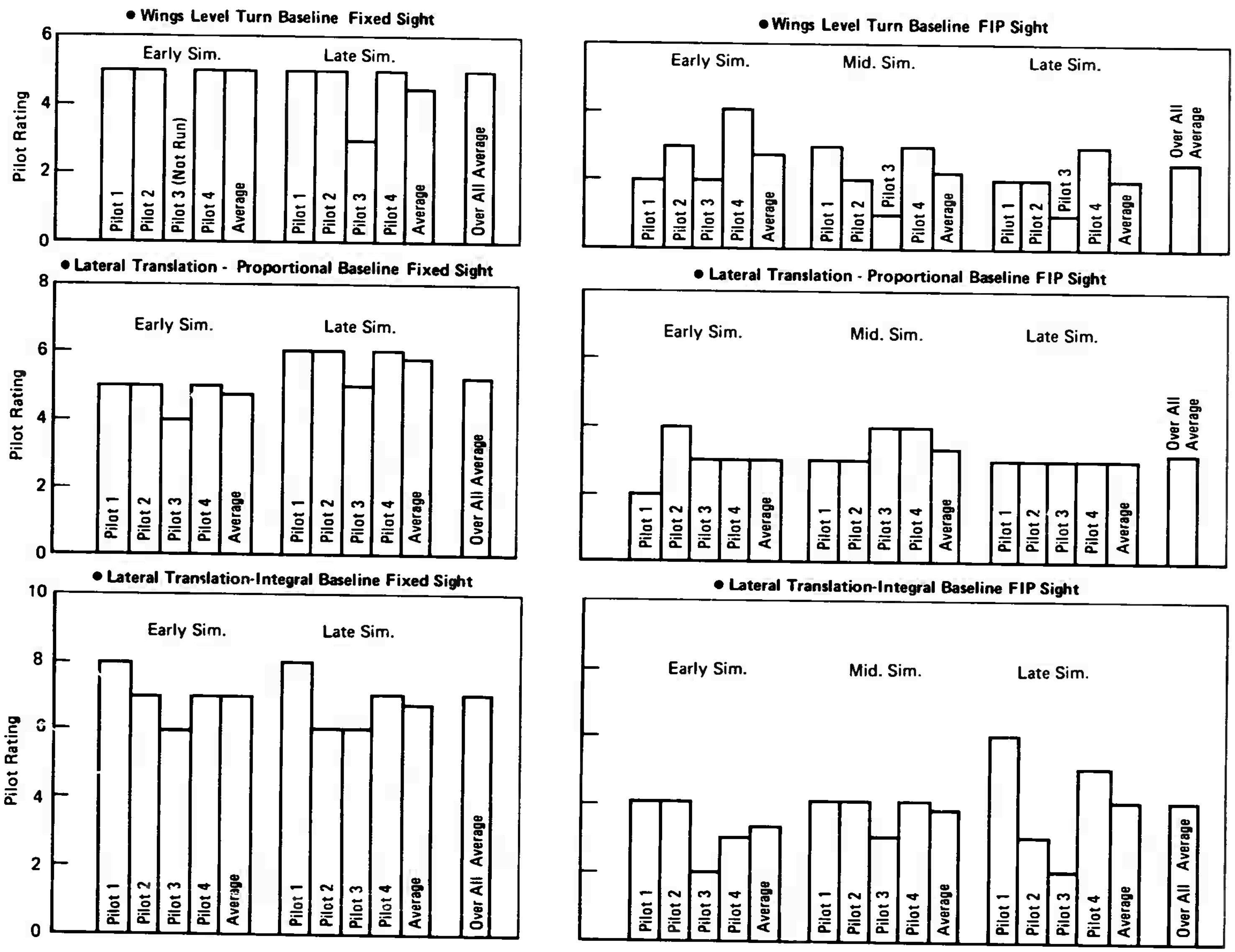
Effects of Learning - All of the baseline configurations were tested in several groups of 5 runs each, corresponding to early, middle, or late in the simulation. These runs were made to identify the effect of learning on the part of pilots and continually give them a base for rating the various configurations. The baseline DSFC modes results are shown on the facing page.

The WLT mode was quite easy to use with the fixed sight and was rated as the best of the fixed sight DSFC modes by the end of the simulation. The reason for the worse than Level 1 rating even for this mode was that the pilots considered the fixed sight bombing task to require considerable pilot compensation.

The LT modes were clearly useless for the bombing task with a fixed sight since large side velocities could be attained before becoming evident, causing large overshoots of the target. The LT-I mode was the worst in this respect since side velocity continued to increase as long as rudder pressure was maintained. With the LT-P mode, the side velocity was proportional to rudder pedal deflection and could therefore be eliminated by centering the rudder pedals. The overshooting tendency of the LT-I was evident immediately, which accounted for the uniformly bad ratings throughout the simulation. It took some familiarity with the LT-P mode for the overshooting tendency to become evident; therefore, the pilot ratings at late simulation were higher than early simulation.

All FIP sight ratings were much lower than the fixed sight ratings. As the pilots gained familiarity with the WLT mode, their ratings generally improved. No definite trend was evident with the LT-P mode. As pilots became more familiar with the LT-I mode, they detected a certain unpredictability of that response which caused them to increase their pilot ratings at the late simulation. The overshooting tendency associated with the fixed sight LT modes did not exist with the FIP sight since any change in side velocity was immediately evident. This is due to the fact that the FIP sight pipper is "tied" to the velocity vector and moves across the HUD in response to any side velocity changes.

Effects of Learning on Pilot Ratings



DSFC DESIGN CRITERIA

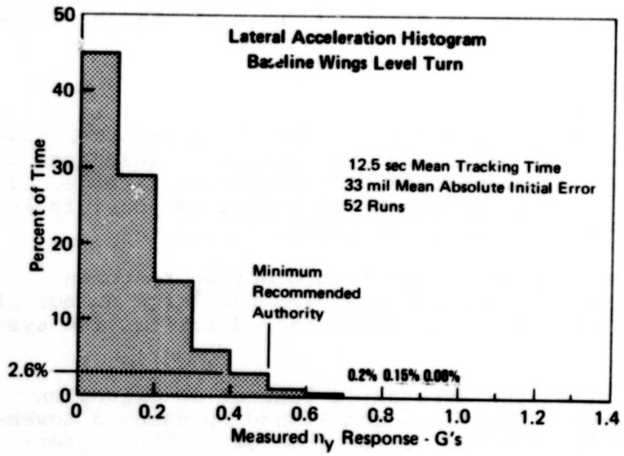
DSFC design criteria presented are based primarily on the pilot ratings and comments, analysis, and to some extent, on bombing accuracy statistics. In many cases, significant differences did not exist in bombing accuracy between configuration variations. Apparently, the task workload was such that increased pilot compensation could overcome configuration deficiencies. The criteria are formulated for the WLT mode, the LT-I mode, and the LT-P mode for dive bombing a stationary ground target using an advanced bomb sight.

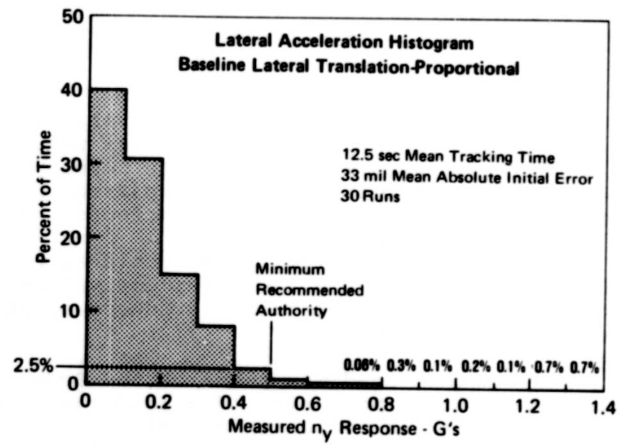
Many of the criteria are applicable to the entire group of DSFC modes tested. Other criteria are only applicable to a specific DSFC mode such as the WLT mode. Criteria can be in the form of limits or in the form of recommended values or design goals. Both forms have merit and, where possible, design goals as well as maximum or minimum limits are recommended.

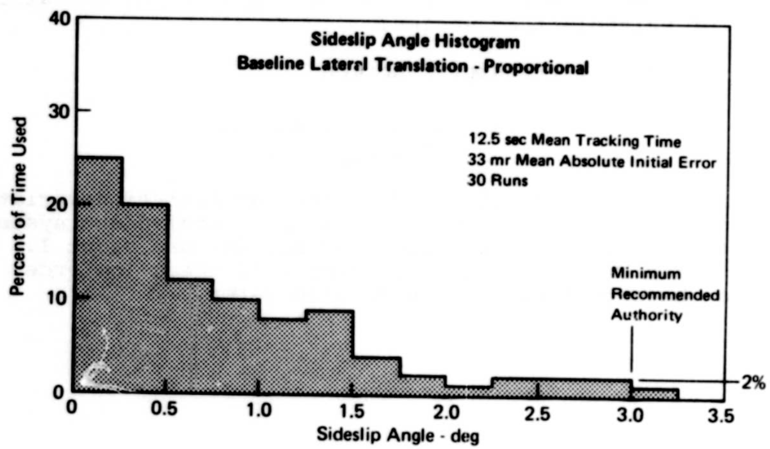
The design criteria presented were arrived at considering the results of this simulation and also extrapolating these results to possibly a more demanding dive bombing task under actual combat situations. For example, DSFC could be used to quickly acquire a target so that the pilot can designate it and perform a pull up along the target/velocity vector until bomb release. The quick acquisition of the target under these conditions is expected to require more DSFC capability than was used under the more mundane dive bombing conditions simulated by this test.

Lateral Acceleration and Sideslip - Histograms of n_y response for the baseline WLT and LT-P modes are shown in the upper two charts of the facing figure, and the sideslip response for the LT-P mode is shown in the lower chart. These histograms show the percent of time a given range of n_y or β response was used during the dive bombing pass. The tracking time shown is measured from the point of roll out (defined as the point in time where bank angle decreases below 12°) to the point of bombs release. These histograms were used in the determination of n_y and β authority, required for useful DSFC, and the results incorporated in the succeeding design criteria.

DSFC Histogram Data







DSFC DESIGN CRITERIA (CONTINUED)

Lateral Acceleration Response Criteria Development - The FIP sight DSFC tracking problem is primarily related to the response of the velocity vector to rudder pedal inputs. The azimuth angle between the pipper and the target is identical to the azimuth angle between the velocity vector and the target. For a constant airspeed, rate of change of the azimuth angle, $\dot{\sigma}$, is proportional to n_y.

$$\dot{\sigma} = \frac{G}{V} n_y$$

Lateral acceleration response variations were tested for the WLT, LT-I and LT-P modes. Although the variety of responses was wide for a single study, the number of responses is quite limited when it comes to the development of generalized DSFC response criteria. It was decided, therefore, that the n_y response criteria should be as simple as possible and be related to parameters widely accepted as system response criteria.

The goal of simplicity was achieved by approximating the high order n_y response characteristics with a low order equivalent system, thereby replacing the large number of poles and zeros with a greatly reduced equivalent set which accurately describes the system response characteristics.

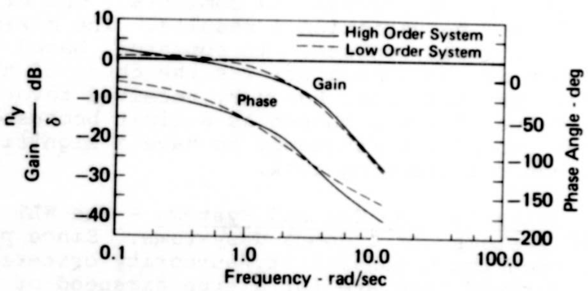
The method used was to match the Bode plot of the aircraft's lateral acceleration response, with a Bode plot of a low order system. This is accomplished by using a Rosenbrock digital direct search algorithm to minimize the sum of the squares of the differences in magnitude and phase between the low order system and the aircraft's high order system at a number of suitable frequencies.

The low order equivalent transfer function

$$\frac{n_y}{\delta} = \frac{s + a}{S^2 + 2\zeta_y \omega_y S + \omega_y^2}$$

was found to accurately represent all DSFC lateral acceleration variations tested. The facing figure pictorially presents how this low order equivalent system was developed. Generally, it was found that the lead time constant (a) was about 1.8 for WLT, approached ∞ in LT-I, and was 0 for LT-P. Further discussion of these low order system transfer function values and characteristics are presented later.

Lateral Acceleration Response Criteria Development



The high order DSFC n_y/δ frequency responses were matched closely using a simple, low order transfer function

Low Order Equivalent Transfer Functions

Wings Level Turn

$$\frac{n_y}{\delta} = \frac{K_1\,(S+a)}{S^2 + 2\,\zeta_y\,\omega_y\,S + \omega_y^2} \qquad a \approx 1.8$$

Lateral Translation - Integral

$$\frac{n_y}{\delta} = \frac{K_2\,(S+a)}{S^2 + 2\,\zeta_y\,\omega_y\,S + \omega_y^2} \qquad a \to \infty$$

Lateral Translation - Proportional

$$\frac{n_y}{\delta} = \frac{K_3\,(S+a)}{S^2 + 2\,\zeta_y\,\omega_y\,S + \omega_y^2} \qquad a \to 0$$

The terms ζ_y, ω_y and a varied.
Criteria were developed in terms of ζ_y, ω_y and a.

DSFC DESIGN CRITERIA (CONTINUED)

Lateral Acceleration Response Criteria - The values of a, ζ_y and ω_y from the baseline WLT configuration, and shown in the left chart, were chosen as design goals, since this configuration received the best pilot ratings and comments. The minimum damping ratio value of 0.3 was based on the WLT n_y variation 4 results. The maximum limit of 4.0 for the constant a, was rather arbitrarily chosen. It appeared, based on the LT-I mode results, that $a \to \infty$ (a pure gain in the numerator) was the cause of the somewhat unfavorable pilot ratings for this mode. The WLT mode, however, received favorable pilot ratings with a value of 1.8 for a. The value of 4 was chosen as a limit because it was felt that values greater than that would have too high a frequency to have a significant effect on pilot opinion for a rudder pedal control tracking task.

Sensitivity/Authority Criteria - n_y Command Systems - The WLT and LT-I modes are essentially n_y command DSFC systems (or $\dot{\sigma}$ command systems. Since pipper rate, $\dot{\sigma}$, is the primary tracking parameter then the G sensitivity/authority criteria is directly related to airspeed. The criteria derived here are for a true airspeed of 480 kts.

The LT-I mode n_y response characteristics were not as good as the WLT mode characteristics, due to, as discussed above the lack of a lead turn in the n_y/δ transfer function. With the less predictable response exhibited by the LT-I mode, the low rudder pedal sensitivity acceptable for the WLT mode was felt to be a bit too sensitive for this mode even though both modes had the same maneuver gradients. This sensitivity of the LT-I mode was also manifested in the bomb impact statistics results with the pilots bombing range error decreasing significantly as the rudder sensitivity was decreased.

The 17.5 lb/deg/sec for the LT-I mode is equivalent to 38.5 lb/G at 480 KTAS. The baseline WLT gradient also was 38.5 lb/G. The authority/sensitivity variation tests produced the following results. The 38.5 lb/G appears to be closest to being universally liked. The 110 lb/G is approaching the area which some pilots felt required too much effort. The 25 lb/G region (21 lb/G in Phase II, 26 and 28 in Phase I), although liked by some pilots was judged too sensitive by others, especially for the LT-I mode. The design goals and level 1 flying qualities limits selected and shown in the facing figure were based on this premise.

Authority criteria recommendations are based on the histogram data shown on page 40. It appears that a minimum of 0.5 G lateral acceleration capability is needed. Higher bombing speeds, shorter tracking time or different dive bombing approaches may require greater authority. The 0.5 G capability should be considered at this time to be the absolute minimum for useful DSFC. A design goal for authority is recommended to be double the above, due to lack of definitive data at this time.

Lateral Acceleration Response Criteria

$$\frac{n_y}{\delta} = \frac{K\,(S+a)}{S^2 + 2\,\zeta_y\,\omega_y\,S + \omega_y^2}$$

Design Goals

- a should be 1.8
- ζ_y should be 1.6
- ω should be 2.0

Limit Criteria - Level 1 Flying Qualities

- ζ should be greater than 0.3
- a should be less than 4.0

Rudder Pedal Sensitivity/Authority Criteria - n_y Command Systems

- WLT and LT-I Modes are n_y Command Systems

Design Goals

- 38 lb/G Rudder Pedal Gradient
- 1 G n_y Authority

Limit Criteria - Level 1 Flying Qualities

- Maximum Rudder Pedal Gradient of 110 lb/G
- Minimum Rudder Pedal Gradient of 20 lb/G
- Minimum n_y Authority of 0.5 G

Rudder Pedal Sensitivity/Authority Criteria - σ Command System - The LT-P mode is a turn angle command system where the turn angle σ, is proportional to rudder pedal displacement. The turn angle is obtained by sideslip angle, β, rather than by changing heading at zero sideslip as would be done for a WLT mode. However, a σ command WLT mode could easily be mechanized. The criteria derived here, although based on LT-P results, are therefore extended to any σ command system. The term σ is used here in place of β for purposes of generality.

The sensitivity (maneuver gradient) appears to be strongly related to the response characteristics. When the baseline mode ($\zeta_y = 1.07$ and $\omega_y = 2.3$) was tested in Phase I, 6.4 lb/deg (F_{rud}/σ) was felt to be too sensitive. In Phase II, 6.9 lb/deg was liked with $\zeta_y = 1.4$ and $\omega_y = 1.83$ (β response variation 1). The 17.5 lb/deg gradient tested was too heavy, while the 8.8 and 9.6 lb/deg gradients were liked.

Based on the above results, the rudder pedal gradient design goals shown in the facing figure, are recommended. A $\zeta_y = 1.2$ was chosen as the rudder pedal gradient boundary since it is approximately halfway between ζ_y for the baseline LT-P response and the β response variation 1. Pilot comments on the tiresome nature of having to hold in rudder pedal pressure to maintain a DSFC σ correction would indicate that the preferable way to go would be the higher damping lower maneuver gradient design goals shown in the upper chart.

A histogram of σ response on page 40 shows that up to three degrees (52 mr) was used a significant portion of the time. Considering the long tracking time this would probably be an absolute minimum for useful proportional DSFC. A recommended design goal would be larger than this, say 50% larger for lack of any substantiating data. Therefore 4.5° was selected as the design goal. Despite the difference in n_y response characteristics between the LT-P and WLT modes, the n_y histograms are quire similar (see page 40). In view of this, the n_y authority criteria recommendations for σ command systems are the same as for the n_y command systems previously discussed.

DSFC Frequency and Damping Ratio Criteria - The pilot ratings of several WLT n_y variations and the $\tau_2 = 0.6$ prefilter time constant variation could be plotted as a function of either damping ratio at nearly constant frequency, or as a function of frequency at nearly constant damping ratio. The low order system parameters values and the plot of the pilot rating versus damping ratio and frequency are shown on the facing figure lower chart. Variation 4 is shown on the damping ratio plot since it is felt that $\zeta_y = 0.3$ may be the critical parameter even though the frequency is not consistent with the other data. No upper limit of damping ratio was found. The baseline configuration ($\zeta_y = 1.58$) received the best rating. No limits were found on natural frequency. The conclusion drawn from these results is that the pilots are relatively insensitive to variations in WLT lateral acceleration response characteristics.

Rudder Pedal Sensitivity/Authority Criteria

σ Command System

Design Goals

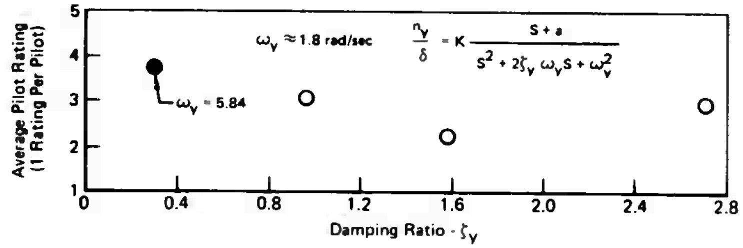
- 7 lb/deg Rudder Pedal Gradient When $\zeta_y > 1.2$
- 10 lb/deg Rudder Pedal Gradient When $\zeta_y < 1.2$
- 4.5 deg Turn Angle Authority
- 1 G n_y Authority

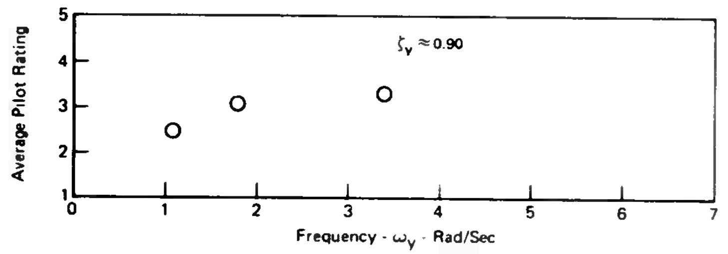
Limit Criteria - Level I Flying Qualities

- 17 lb/deg Maximum Rudder Pedal Gradient
- 6 lb/deg Minimum Rudder Pedal Gradient When $\zeta_y < 1.2$
- 3.0 deg Minimum Turn Angle Authority
- 0.5 G Minimum n_y Authority

DSFC Frequency and Damping Ratio Criteria

WLT n_y Variation	Low Order System Parameters a	ζ_y	ω_y
1	1.8	2.7	1.71
Baseline	1.7	1.58	2.00
2	1.7	0.96	1.80
3	1.7	0.80	3.33
4	3.9	0.30	5.84
$\tau_2 = 0.6$ (Prefilter Variation)	1.7	1.05	1.07





DSFC DESIGN CRITERIA (CONTINUED)

Sideslip Coupling - The sideslip limit criteria stem primarily from the bombsight dynamics. These results should be valid for any computing bombsight where the pipper is tied to the velocity vector.

The recommended limits on sideslip coupling, in terms of β/n_y are weighted heavily towards pilot one's comments which are plotted separately in the upper left chart. The piloting technique of pilot one is certainly representative of a sizeable group of pilots. Flying qualities characteristics should therefore be such that the closed loop response characteristics are acceptable for this group of pilots. A reasonable fairing through the pilot ratings of Pilot one indicated that a β/n_y of -2 deg/G should be the limit for level 1. Of course, the design goal would be $\beta/n_y = 0$.

No positive sideslip limits were found but gunnery requirements would obviously dictate that the nose initially move in the direction commanded, i.e.; $\beta < \dot{\sigma}$.

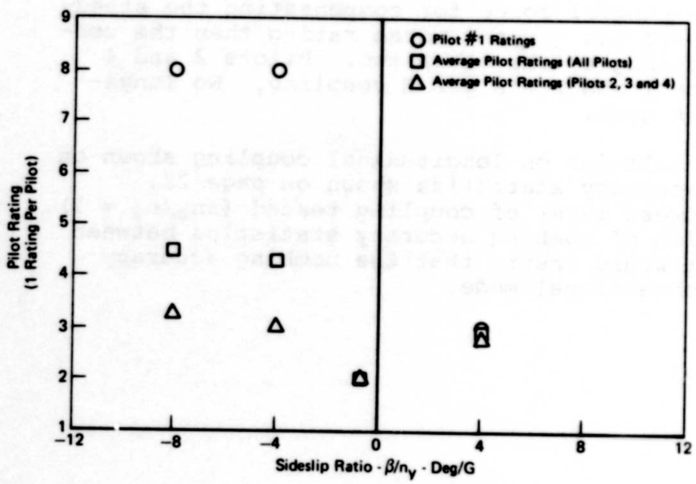
n_y Command DSFC Roll Coupling - It is recommended that negative roll coupling, expressed as a ratio of roll rate to yaw rate (p/r) be prohibited. Pilots 1 and 2 were of the strong opinion that this type of coupling would be dangerous and pilot 3 allowed that in a real aircraft the effects of negative coupling may be worse than in the simulator. The average pilot ratings are shown in the upper right chart.

No positive roll coupling limits based on the pilot opinion were found, but bombing accuracy results shown on page 24, indicate that an accuracy degradation was evident with the p/r = 12 coupling variation. The recommended positive limits are therefore p/r = 8. This limit is liberal enough so as not to present any compliance problems. The design goal for roll coupling would be zero.

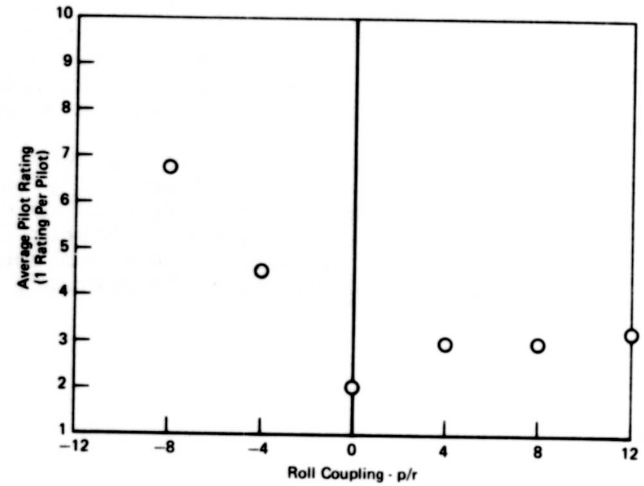
The recommended lateral directional coupling criteria are summarized in the lower chart.

DSFC Lateral Directional Coupling Criteria

• Sideslip Coupling – Wings Level Turn



• Roll Coupling – Wings Level Turn



Design Goals

- No Sideslip on Roll Coupling

Limit Criteria - Level 1 Flying Qualities

- Maximum Permissible Negative Sideslip Coupling, β/n_y, Should be −2 deg/G
- $\dot{\beta}$ Should be Less than $\dot{\sigma}$ for Positive Coupling
- No Negative Roll Coupling (p/r)
- Maximum Positive Roll Coupling Should be 8

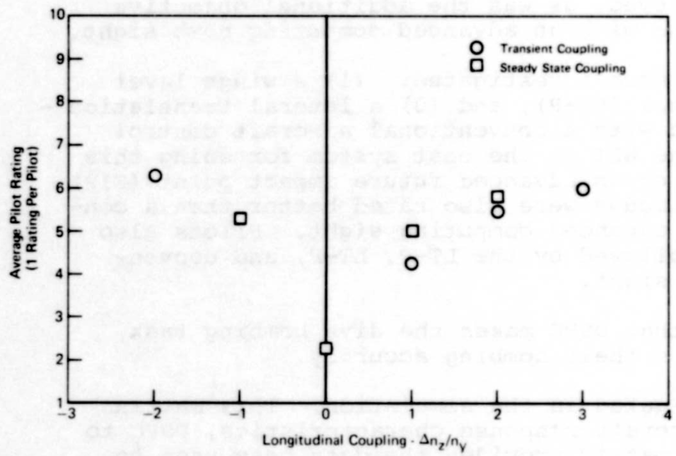
DSFC DESIGN CRITERIA (CONCLUDED)

Longitudinal Coupling - Steady state coupling was rated as being slightly worse than transient coupling. Pilots found they could ignore the longitudinal oscillation of the transient type, but they actually had to apply a control force for compensating the steady state coupling. One G per G transient coupling WLT was given a worse rating than the conventional mode by 2 of the pilots and a better rating by the other two. Pilots 2 and 4 objected least to the coupling, at least for, the 1 and 2 G's per G coupling. No longitudinal coupling at all is the recommended design goal.

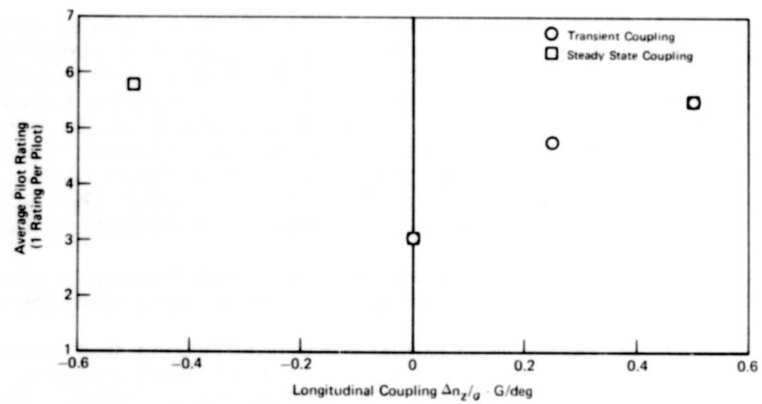
The recommended limits for level 1 flying qualities on longitudinal coupling shown on the facing page are based primarily on bombing accuracy statistics shown on page 22, which were significantly affected by even the lowest level of coupling tested ($\Delta n_z/n_y = 1$). The values were determined by linear interpolation of bombing accuracy statistics between $\Delta n_z/n_y = 0$ and choosing a level of coupling that would insure that the bombing accuracy would remain better than the accuracy for the conventional mode.

DSFC Longitudinal Coupling Criteria

- **Longitudinal Coupling – Wings Level Turn**



- **Longitudinal Coupling – σ Command System**



Design Goals

- No Longitudinal Coupling

Limit Criteria - Level 1 Flying Qualities

- Longitudinal Coupling, For n_y Command DSFC Systems, $\Delta n_z/n_y$, Should Be Less Than ±0.3 For Transient Coupling and ±0.2 For Steady State Coupling
- Longitudinal Coupling For σ Command Systems, $\Delta n_z/\sigma$, Should Be Less Than ±0.025 G/deg

CONCLUSIONS

A systematic investigation on the use of direct side force control (DSFC) for dive bombing has been completed. The investigation was conducted in a fixed base simulator and consisted of over 2500 data runs. The objective of establishing design criteria for DSFC response characteristics for dive bombing was achieved, as was the additional objective of measuring the payoff of DSFC used in conjunction with an advanced computing bomb sight.

Three direct side force control flight modes were investigated: (1) a wings level turn (WLT), (2) a lateral translation - proportional (LT-P), and (3) a lateral translation - integral (LT-I). These flight modes were compared with a conventional aircraft control for dive bombing a ground target. Pilots rated the WLT as the best system for doing this task using either a fixed depressed reticle sight or an advanced future impact point (FIP) computing sight. Both lateral translation flight modes were also rated better than a conventional aircraft mode for dive bombing using an advanced computing sight. Pilots also achieved the best bombing accuracy with the WLT followed by the LT-P, LT-P, and conventional flight modes, all using the computing bomb sight.

Analyses of these results conclusively show that DSFC makes the dive bombing task easier and better liked by the pilots, and improves their bombing accuracy.

A large matrix of test conditions was investigated in the simulation. This matrix covered variations in the control feel system, aircraft response characteristics, DSFC to longitudinal coupling and other parameters. This matrix provided the data base used to develop the DSFC design criteria. Some of the more pertinent design criteria along with some general conclusions are summarized on the following two pages. It should be reiterated that these design criteria are based on the results of this particular simulation; however, consideration was given to the impact of a more demanding dive bombing task than was simulated.

Recommended DSFC Design Criteria

- For DSFC lateral acceleration response of the form

$$n_y/\delta = \frac{s + a}{s^2 + 2\zeta_y \omega_y s + \omega_y^2}$$

$a = 1.8,\ \zeta_y = 1.6,\ \omega_y = 2.0$

Level 1 flying qualities limits
  - $\zeta_y > 0.3$
  - $a < 4.0$

- DSFC sensitivity/authority design criteria goals for WLT and LT-I
  - 38 lb/lateral G's rudder gradient
  - 1.0 lateral G's (n_y) authority

Level 1 flying qualities limits
  - Maximum rudder gradient of 110 lb/G
  - Minimum rudder gradient of 20 lb/G
  - Minimum n_y authority of 0.5 G's

- DSFC sensitivity/authority design criteria goals for LT-P
  - 10 lb/deg rudder gradient for $\zeta_y < 1.2$
  - 7 lb/deg rudder gradient for $\zeta_y > 1.2$
  - 4.5 deg turn angle authority
  - 1.0 n_y authority

Level 1 flying qualities limits
  - Maximum rudder gradient of 17 lb/deg
  - Minimum rudder gradient of 6 lb/deg for $\zeta_y < 1.2$
  - Minimum rudder gradient for $\zeta_y > 1.2$ not established
  - Minimum turn angle authority of 3 deg
  - Minimum n_y authority of 0.5 G's

- WLT sideslip coupling criteria
  - Design goal is to have $\beta/n_y = 0$
  - Level 1 flying qualities limit $\beta/n_y = -2$ deg/G
  - No positive sideslip coupling criteria found for dive bombing, however, gunnery would dictate a limit.

- DSFC longitudinal coupling criteria
  - WLT design goal is to have $\Delta n_z/n_y = 0$
  - Level 1 flying qualities limit
    - $\Delta n_z/n_y = 0.3$ for steady state coupling
    - $\Delta n_z/n_z = 0.2$ for a transient coupling
  - LT-P design goal is to have $\Delta n_z/\beta = 0$ G's/deg
  - Level 1 flying qualities limit is 0.025 G's/deg

- DSFC roll coupling criteria
  - No negative roll coupling (p/r = 0)
  - Maximum of p/r = 12 positive roll coupling

General Conclusions

- WLT flight mode was liked best and the most accurate bomb scores were achieved by the pilots with this mode when using either a fixed or FIP bomb sight.
- LT-P and LT-I were rated better, and the bomb scores were better, than a conventional control mode when using a FIP sight.
- Pilots liked the fixed roll stabilized sight and the RLOS better, and their bomb scores were better, than a conventional controlled aircraft with a fixed sight.
- A rudder pedal controller for DSFC was liked by the pilots. A thumb button on the control stick for DSFC was discarded because pilots could not simultaneously use the controller and bomb button.
- A rudder pedal controller appears insensitive to aircraft response characteristics and pilots can adapt to a large range of DSFC characteristics.
- LT-P and LT-I flight modes are impractical for dive bombing when used in conjunction with a fixed bomb sight.

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